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Visualizing the data flow in virtual reality for training developers

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ABSTRACT OF MASTER'S THESIS

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The visual aids are powerful tools in learning, understanding, and retaining data, especially in the industrial sector. However, visualizing data for complex systems is an essential challenge as they need to address a discrete and large amount of data. When novice programmers develop these complex systems, they typically require further training on the data flow in order to understand the hidden meaningful patterns. The visualization of invisible data in virtual reality (VR) helps to explore these patterns and direct new avenues to develop a system in the real world. Thus, the presentation of complex data in a 3D visual form is crucial and effective.

To accomplish this, this research study considers a case scenario of Indoor Air Quality (IAQ) system based on Internet of Things (IoT). By definition, IoT is a multifarious connection of devices and data over internet and thus, needs visualization. A better understanding of how visualization in 3D space can assist programmers to learn IoT concepts. In turn, this poses profound questions in the areas of virtual reality and human-computer interaction. Consequently, the aim of this study was to visualize IoT sensor data in a virtual environment and produce guidelines for programmers in order to help them better comprehend the data flow. Subsequent to this, the level of immersion required for an effective VR experience was also investigated.

Overall, this study involved background research and an empirical study. The semi-structured interviews were conducted with the programmers and was handled as an empirical evidence. This evidence was further analyzed qualitatively. As a result, the static visuals of IoT sensor data values helped the users to understand its flow. The visual clues both from abstract and skeuomorphic designs furthered the users understanding of the concepts. Accompanied by the text, necessary information about the concept was revealed to the end user. The analysis clearly highlights that visualizing in virtual reality enhances the experience by improving user awareness and user engagement level. In addition, this provides a more intuitive understanding of data flow and better recall of the observed relationships.

Keywords:	Internet of Things, visualization, virtual reality
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Abbreviations and Acronyms

3D	Three Dimensional
2D	Two Dimensional
API	Application Programming Interface
ERP	Enterprise resource planning
FIOH	Finnish Institute of Occupational Health
FOV	Field of view
Hi-Fi	High Fidelity
IAQS	Indoor Air Quality System
IoT	Internet of Things
JSON	JavaScript Object Notation
Lo-Fi	Low Fidelity
PM (2.5, 10)	Particulate Matter
RFID	Radio Frequency Identification
Sci-Fi	Science Fiction
SLR	Systematic Literature Review
UI	User Interface
VEoT	Virtual Environment of Things
VR	Virtual Reality
VOC	Volatile Organic Compounds
WAN	Wide-Area Network

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Chapter 1

Introduction

In the past decade, the need for visualizing data in a comprehensive style has significantly increased. The need arises with the tremendous efforts taken in the data industry to unfold the complexity of the existing load of information. The well-depicted visualization plays a crucial role to quickly process the data. In addition, this provides clear understanding to the user, which is very well elaborated in the research - Ward (2015). The author believes that properly depicted visuals can provide better avenues to solve problem and effectively analyze data. Likewise, according to Brunhart-Lupo et al. (2016), visualizations present the raw data into more human understandable information. This further enables user to make productive decisions based on recognized patterns.

Although there are many kind of technologies to enable and provide visualizations in an appropriate format. One of the emerging technology is virtual reality (VR) which can amplify the benefits of visualization as it provides a simulated environment that might reflect similarities to the real world. For example, the user can travel from one part of the world to another from the convenience of one's home or visualize the timeline of stock market in a form of ladder. The former example renders the real world image with motion inside VR. Whereas, the latter example allows the user to walk down or up the ladder based on his/her actions. Thus, a simulated environment, that is, VR can provide visual abstracts and clear statistics.

In addition, immersion provides a better perception of a datascape geometry, more intuitive data understanding, and a better retention of the perceived relationships in the data as per the theory stated in Donalek et al. (2014). The immersive VR places the user in the virtual environment (VE), a virtual scenario, and detaches them from the real world interaction. this is further proved by Teasley and Wolinsky (2001). In regard to provide an immersive experience, the purpose of VR application defines the level of immersion - low level or high level. Since it provides a new reality experience, the user might fear the technology. This fear might also lead to usability issues and thus, complicate the experience.

Several examples are available where VR can enhance one's experience and help to deal with various problems. In the beginning, VR provided applications in the entertainment, gaming, and medical industries. However, later on, the experience was shared beyond fantasy and into the corporate life. One of the proven domains is enabling organizations train novice employees in safety-critical situations. The challenge arose due to the risks involved in the actual environment. For instance, training programs in a military, construction, and aviation requires real life work scenarios. Thus, VR applications simulating actual work environment are implemented to enable trainees to practice in life-critical tasks.

Similarly, there has been explorations of many other domains which are applicable for VR as technology and one of them is Internet of things (IoT). This is a popular domain where VR collaborates with products connected over the internet. It shares a basic philosophy with IoT. In relation to the outcome of both the technologies, the fundamental basis of virtual reality is to portray the digital world as real. Whereas in IoT, the devices from the real-world are manipulated in such a way that they are flexible in the digital world. Currently, real-world objects operates with different interfaces. This provides different visualizations and thus, different experiences for the end-user. Thereafter, creating challenges for the end user to analyze and understand the data.

Consequently, numerous studies share that there is a potential use of immersive technology in IoT field. For example, the possibility of virtual sensors, immersive 3D environment known as Prototypical virtual environment of things (VEoT) - Alessi et al. (2016), virtual reality utilized as a visualization platform, and VR binoculars, which is a digital visualization framework that operates in real time, as proposed by Toumpalidis et al. (2018).

A classic IoT solution consists of a complex mix of IoT endpoints, platforms, back-end systems and data (For example, sensors, actuators, processors, embedded software, local and long range connectivity, middle ware, apps, analytic, and machine learning) that flows seamlessly across interfaces, as shared by Mendix (2017). Once these multiple data types from several devices are together, the end user needs to access a simple yet informative visualization. The end user can access the data on any interface they want, such as a phone, laptop, or big screens in a workplace. Different users, such as an owner, financier, and technician, should have access to their own information. With such diversity at many levels, the interaction between a user and the product becomes difficult. There are different factors in parallel to interaction, such as usability, accessibility, and fun which effects the overall satisfaction level of the user. The process to identify and work on these improvements is known as User experience (UX) design. Since IoT solutions are complex, the UX design becomes complex too.

In order to better understand with a real time example, consider a typical IoT solution in a smart home scenario. This includes smart devices and electronic gadgets connected over the internet. Here, the data is exchanged, analyzed, and presented on the user dashboard using IoT technology. The correct operation of the development and maintenance stages involve a stackful of layers. This in return reflect on different interfaces and visuals - thus, creating inconsistent user experience problems on broad areas.

Likewise, a narrow focus on interactive products might not help because they do not capture the incongruent aspects emerged from the smart technology. The practitioners and researchers, together seem to encircle the UX approach instead of Human-Computer Interaction (HCI). Moreover, Mineraud et al. (2016) studied the loopholes of current IoT platforms. This analysis signifies the need to improve visualization, cross-platform interaction, data management, privacy, and views from all stakeholders. In the direction of improving visualization, understanding the visual content is important. This is followed by, enhancing the user awareness and user engagement level. The consumers are not familiar with the technology around them in public locations. These highly sophisticated machinery might capture physical analytics within the environment in which they inhabit. Later, these analytical data is leveraged to companies so as to provide new knowledge about the consumers. Finally, this could affect people's lives in uncertain terms. This leads to unsatisfied user experience, frustration, mistrust, and poor levels of adoption as a result of an inability to capitalize on benefits, as per Mikusz et al. (2018).

In a nutshell, visualization in VE provides an effective environment where one can learn the concepts by performing the required actions within the VR space. This is supported by Kreis et al. (2018) who trace the benefits of VR applications, especially, in an area on how to spread knowledge. As VEs provide the possibility to interact with the information. The translation of training experiences into real world skills might also be possible. Moreover, this opens up the route to research more in the field of immersive visualizations. Henceforth, studies of visualization in 3D environment might improve the learning process in an effective way. Correspondingly, the hypothesis for this study are the positive impact of learning through the aids of visuals in 3D environments. Since the 3D environment demands immersion, it is noticed that a certain level of immersion is suitable for certain applications. This principle might not only help in improving one's grasping power but also in helping them to remember data for a long period of time. However, for the

RQ1	How visualization in virtual reality help to understand the flow of (IoT sensor) data?
A	What is the level of immersion required to understand (IoT sensor) data?
B	What are the advantages and disadvantages of VR based visualization?

Table 1.1: Research questions

scope of this prototype, only the data flow of an IoT system was visualized in virtual reality.

This thesis aims to address how IoT data is depicted in a virtual environment and how users comprehend the visuals in order to determine appropriate guidelines for optimizing the user experience. The focus is also to enable the user to have an enhanced experience in an engaged form. Finding the right level of immersion will help achieve the goal. In addition, the findings from several studies, such as Kaasinen et al. (2015) are also collated together to identify the issues derived from certain technology, especially in terms of UX. Applying a similar approach, this study consists of two parts : prototype implementation and empirical study. After studying the latest materials on related topics, a possible approach of constructing a high fidelity prototype was chosen and implemented. Further on, interviews with five users took place before and after interacting with the prototype. In pursuance of learning the IoT technology and virtual reality, experts from the corresponding industry were interviewed, and the insights were noted.

The insights were constructed during the research phase. Research questions were formulated, as shown in Table 1.1. The primary research question RQ1 is divided into two main sub questions A and B.

The remainder of the thesis continue as follows : “Chapter 1” unfolds the research question by introducing the various concepts and terms required to obtain an overview of the thesis title, followed by “Chapter 2” that describes the academic background required to understand the concepts related to the thesis topic. This chapter starts with an overview of three different topics: UX, IoT, and VR and it ends with an explanation of the core focus of the thesis title. In order to implement these theoretical concepts into practical procedure, “Chapter 3” describes the scientific method applied to gather the requirements, trace the design and prototyping process. In addition, this chapter addresses the important points to consider while preparing for interviews, and analyzing qualitative data. Further on, “Chapter 4” summarizes all the results obtained from prototype test, user interviews, and analysis of the findings. The aim to include the analysis in this chapter is to provide evident reasons for all the three research questions. Similarly, "Chapter 5" discusses the outcomes from the previous chapter so as to answer the research questions in an appropriate method. This chapter also acknowledges the findings from the other research studies that were observed in the previous chapters. It reflects on the positive and negative impacts of the visualizing in VR. However, there were few restrictions noticed during this research along with the possible future recommendations and thus, they are all mentioned in "Chapter 5". Finally, "Chapter 6"concludes that visualization in VR helps to understand the flow of data, if implemented properly with appropriate immersion level.

Chapter 2

Conceptual Background

This section illustrates the previous research conducted on the user experience perspective of IoT ecosystem. This section also addresses its relation to virtual reality. The concepts emerging from the research questions, as stated in table 1.1 are explicitly defined and discussed in this chapter.

2.1 User experience

2.1.1 Definition

Over the years, the word "user experience" (UX) has evolved through experts opinion and still misses a formal proper definition. In business world, different definitions of UX may perplex consumers of a product or service. This might also mislead them and weaken the active efforts taken by researchers and academicians. The term *User experience* was described as all aspects of the end-user's interaction with the company, its services and its products combined together by Don Norman and Jakob Nielsen, in Walton (2015). The UX field is multifaceted, incorporating different aspects on knowledge and techniques from a range of academic and commercial areas. Numerous attempts have been practiced to promote a common protocol on the nature and scope of UX. Due to the recentness and novelty of the concept, it is hard to come to an agreement.

However, the *international standard ISO 9241-210*, Ergonomics of human-system interaction, defined UX as a "persons perceptions and responses that result from the use or anticipated use of a product, system or service", ISO (2010). Based on Hassenzahl and Tractinsky (2011) thoughts, UX is influenced by "user's internal state (predispositions, expectations, needs, motivation, mood, etc.), the characteristics of the designed system (example, complexity, purpose, usability, functionality) and the context (or the environment) within which the interaction occurs (For example, organizational/social setting, meaningfulness of the activity, voluntariness of use)"

Initially, user experience was mainly about providing features checklist or fulfilling users' wants. At present, true user experience is considered when user needs are met along with seamless integration of different services from different disciplines, including engineering, interface design, business management, and industrial design. The UX design process encloses every touch point of the user while interacting with the system, virtual or physical. The overall aim is to create meaningful and relevant experience for the user. Recently, a thorough study was carried out by Bakioglu (2018), to measure the return on investment (ROI) for UX in enterprise organizations.

Traditional HCI focuses on achieving behavioural goals during the usability test of the system. The user experience has evolved from HCI focusing on positive outcomes and developing quality experiences instead of resolving usability problems. This is further accomplished by considering wider boundaries of user satisfaction and competitive differentiation. Hassenzahl (2018) consider *designing for pleasure* rather than *absence of pain* theory as a part of future UX design.

According to Hashim et al. (2018), UX is considered as a subjective intellectual in universal concept that strongly touch the usability aspects of the user, the value sensitive design, social and cultural communication, and emotional including experience such as fascination, joy, excitement, and aesthetics. As a result, similar concepts revolving around the various aspects of UX were considered to bring forth the core concept that best suits this research.

2.1.2 Related concepts

Over the years, many attributes and terms are created around user experience. These components vary based on end-purpose, context, and scale. Here, scale is referred to the specific and/or general level of analysis during the interaction between the user and the system. For instance, according to Hassenzahl (2018), usability belongs to more formal evaluative category than UX which is a combination of multiple values. UX provides an overall view concerning the quality of the system and its impact on an end-user. The figure 2.1 narrates detail aspects of UX and usability goals. The goal of designing interactive systems primarily concerns with creating the systems that are fun, aesthetically pleasing, satisfying, enjoyable, helpful, motivating, and so on as explained in the figure 2.1. These goals improve the quality of user experience whereas usability goals are more focused on efficiency of the product, utility, and safety of the product allowing the user to learn well and optimize the overall interaction with the system, as mentioned in Preece (2002). The usability goals plays a central role in the interaction design cycle and are rationalized through a specific criteria. Subsequently, the user experience goals are less clearly defined and embraces every aspect as shown in the outer circle in the figure 2.1.

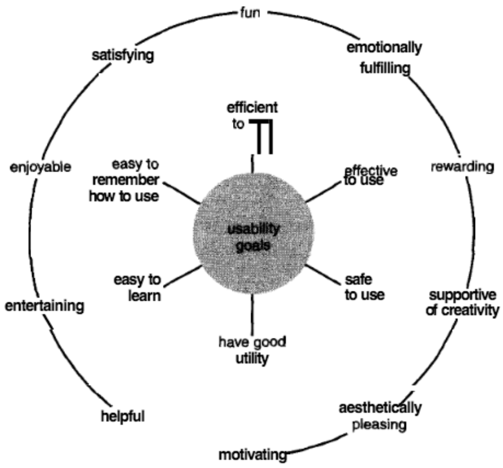

Figure 2.1: User experience and usability goals

The user emotion plays a central role in user-experience. It describes the bond formed between an individual (consumer or end user) and product or service. Designers usually focus on achieving positive emotional outcome in a form of experience as proposed by Hassenzahl (2018). However,the user awareness and user engagement from Hartson and Pyla (2012) research study are a few main attributes of UX that will be discussed further in the study. The Curry et al. (2018a) study explains the importance of having an effective user experience within a smart environment for its success. Here, smart environment means smart buildings, smart cities, smart energy management system and the list goes on. The author investigated user awareness and user engagement attributes from human-computing interaction phase. Their assessment helped to find the users' actual needs. Consequently, user interaction, as referred in Hartson and Pyla (2012), must be considered within a context or environment shared between the system and the user. The input actions can be controlled by user or system and it will still be called as user-system interaction. For example, a smart wall, a wall with ambient intelligence, can proactively extract inputs it needs from a user by sensing user's presence and identifying the user with something like radio-frequency identification technology instead of just responding to a user's input actions, as shared in Hartson and Pyla (2012).

The UX design process, as referred from Bergman and Johansson (2017) academic paper, is divided into four phases : analyze, design, prototype, and evaluate. This is an iterative cycle along with multiple repetition of each phase. Additionally, Preece et al. from Preece (2002), Arvola (2014), and Hartson and Pyla (2012) briefly described each of these phases in their respective studies.

A qualitative data representation guide user to understand data in an effective and easy manner. Moreover, to view a problem in a structured format, the availability of sources to visualize these format plays an important role. A clever visual representation will help to communicate a complex message to a diverse crowd. Once we understand how our eyes processes these complex visuals, we will find our-self at better position to arrange elements more effectively. The authors from Dalton (2016), and Donalek et al. (2014) proves that once our brain understands the method of processing visual elements, it becomes easier to arrange these elements in an effective way.

This thesis will consider the holistic approach of understanding UX issues of the user during the review. In regards to aggregated view, Owen (2007) introduced a few capabilities that designers should adopt, including a perspective focusing on humans and surrounding environment, a tendency toward versatility, a subjective use of language, a friendly bond for good teamwork, a combination of potential components instead of making a decision among the imperfect and inflexible answers, and communicability through visualization Dalton (2016), Donalek et al. (2014). Although, constraining to the scope of thesis, user engagement and user awareness were main focus of this study. The underlying facts and reasons for the same are explained clearly in the section 2.2. This section also explains the need of IoT context combined with user engagement and user awareness subjects.

2.2 Internet of Things - (IoT)

IoT is a growing technology due to the accessibility and availability of internet and connected devices. This technology enables us to interconnect the physical world with digital using devices, sensors, and actuators. The data is accumulated using devices and it's sensors. This data is processed and translated into commands which are further executed using actuators. The International Telecommunication Union (ITU) defines IoT as "a global infrastructure for the information society, enabling advanced services by interconnecting physical and virtual things based on existing and evolving interoperable information and communication technologies." as clearly stated in paper written by Bergman and Johansson (2017) and ITU-T (2016).The Cluster of European Research Projects on the Internet of Things (CERP-IoT) defines it as "a dynamic global network infrastructure with self configuring capabilities based on standard and interoperable communication protocols where physical and virtual things have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network" as referred in Bergman and Johansson (2017) and Harald Sundmaeker et al. (2010).

In 2020, 20.8 billion devices are estimated that to be connected via the internet according to Gartner, Inc Fraifer et al. (2017). The IoT based companies are trying to integrate machine learning technologies in their platforms to provide intelligent, personalized, and engaging user experience. These IoT solutions are built by a combination of different types of developers providing their expertise across edge computing, platforms, web-services, mobile applications, data analysis distributed in multiple tiers. The edge tier covers both gathering of data and end-to-end point communication of real-time data between sensors, actuators, and devices.

Three decades ago, Mark Weiser proposed a vision of *ubiquitous computing* in his journal Weiser (1991). This term was carried ahead by science fiction author Sterling and Wild (2005) who envisioned its usage in *Shaping things*. Mobile to mobile communication has evolved from communication protocols to sensory hardware, mobile, and pervasive device, alongside social and cyber-physical networks, resulting in an interesting concept combined with inherent complexities known as *Internet of things (IoT)*, as mentioned by Ahsan (2015). In ideal scenario, IoT will enable users to connect to any *things* placed at any place running over any network/path providing any service, as proved by Chuang et al. (2018). The Radio Frequency Identification (RFID) tags are one of the early examples. The active participation of the users in IoT is highly supported by the widespread distribution of interconnected devices and sensors. According to Munjin (2013) paper, consumers started producing information, data and software to increase business benefits, along with being passive users. A considerable amount of research has been carried out to implement smart applications, such as smart homes as described in Luigi De (2015) study which is based on trigger-action (If This Then That) principle.

The IoT ecosystem provide different touch-points for the end user to participate. These end points communicate with the help of variety of software's to manage device, security, digital twin functionality, API and so on. The developers create and adopt IoT-related applications to perform the corresponding operations. The IoT ecosystem model layer frames IoT devices and services on the basis of their categories (For instance, lighting systems, user devices, smart appliances) and their final capabilities, such as switching, sensing, actuating, and communication. In addition, to consider a real time scenario indoor air quality monitoring (IAQ) system is a good example that as it runs on IoT technology. In addition, there are IAQ sensors which measure the air quality within and around the buildings. They are important and handle air quality systems in an efficient way. Overall, these IoT devices provide functions for sensing and actuating in the physical world. The local and wide area networking provides these with the necessary infrastructure to connect to services, adopting wireless sensor networks to form multi-hop architectures with gateway sensor nodes that provides WAN connectivity towards the back haul network. The IoT ecosystem on high-level are re-

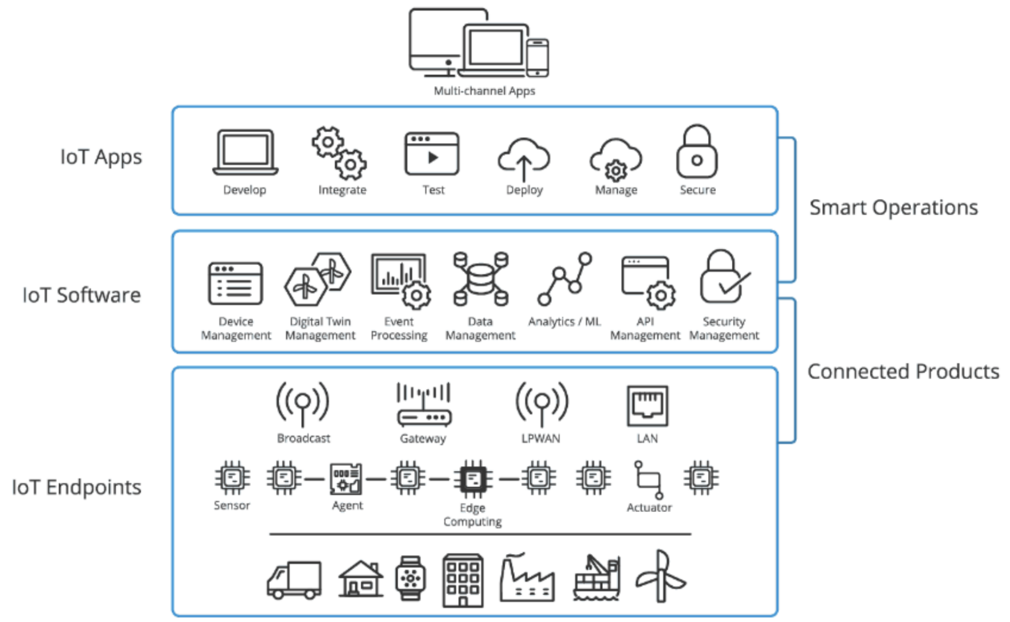

Figure 2.2: IoT touchpoints

ferred on Mendix (2017) and also adapted in this thesis as illustrated in the figure 2.2. The data management handles essential functions such as data acquisition, validation and storage, and makes sure that critical information is available at the right point in a timely manner, and in the right form. Business processes refers to the series of steps to perform management, operational, and supporting activities for achieving specific mission objectives, as referred in Holler (2014). A few academic studies have been focusing on exploring types of IoT applications suitable for enterprise solutions as shown in the research conducted by In Lee Kyoochun Lee (2015). These real-world IoT applications are developed considering its impact on customer value. Enterprise applications are categorized as:

- Monitoring and control
- Big data and business analytic
- Information sharing and collaboration

2.2.1 IoT data

In general, data are raw values or symbols that are untranslated into any meaningful form. They describe a sequence of events without any relation to each other. This raw data is connected together to form a meaning based on the purpose and context, which results as *Information*. Further analysis of information helps to articulate answers for questions like “why, when, what or where”. However, *knowledge* reflects the cognitive processing of information and its match with the existing human knowledge structure, according to Keller and Tergan (2005) research. In IoT, data is produced from the connected objects and their sensors. This data offers the promise of new services, improved efficiency, and possibly more competitive business models.

The data produced by IoT devices provide enormous value only when utilized after it's analysis. Both knowledge and data are the wealth of IoT industry. Invariably, tremendous amount of data is generated from the devices and its sensors which is further sent to a common location-say gateway or the cloud. Here, the data is processed and sent back to the sensors of the devices. Henceforth, the process is imperative to have an efficient way of collecting small amounts of data and processing it to the centralized location, and again sending it back to the sensors - all in real time. The immense explosion in numbers and capabilities of these devices and sensors result in large data size. It's processing can be extremely large (volume), fast (velocity), and diverse (variety)- all the characteristics associated with big data. The role of big data on IoT is massive, but the most visible applications will be in analytic section, data security, and data storage fronts.

Though the value of data in IoT is high, there are problems understanding this data. Especially, when the data is streaming and extracting valuable information from sensors, as also explained in Teachey (2018). Though, there are still issues with stored data that needs to be addressed. From IoT user experience perspective, one of the biggest challenge is unifying all the interfaces communicating across different applications. The IoT product as a whole is a combination of number of visible layers overlaid on invisible layers. Due to the existence of hidden layers, it is difficult to synchronize the interfaces and give a good experience to the user in a single app, as highlighted by Fraifer et al. (2017) research. Moreover, data is represented in different formats and models. Handling raw data offered by sensors without well-structured knowledge model is difficult. It becomes more complicated when new data are generated rapidly both in amount and types. This also explodes the number of ways required to filter, analyze, compare, contrast, interpolate, and extrapolate produced data.

The different varieties utilized to operate with data will affect the whole IoT ecosystem if changed in an inconvenient way. Especially, designers should consider to design for the whole ecosystem and not only a mobile application complied with IoT backend. As IoT is growing on large scale connecting many devices and its sensors, the data provide more opportunities for further applications, and business models. Yet another challenge will be with the companies who want to implement IoT in their current business. They need more skilled business analysts who can use the semi-structured, structured, and raw sensor data into valuable business insights as recently published in Ranjan Pattnaik et al. (2018) report. More IoT-specific skills are required to help companies realize the possible IoT applications for existing products and services. Ranjan also addressed a few other issues like infrastructure, quality of data, choosing software stack, analyzing data and skilled manpower.

There are a few problems faced by the developers of IoT industry. These developers who want to practice IoT products need to negotiate access individually and adapt to the platform-specific API and information models. Having to perform these actions for each platform often outweighs the possible gains from adapting applications to multiple platforms. This fragmentation of the IoT and the missing interoperability result in high entry barriers for developers and prevent the emergence of broadly accepted IoT ecosystems, which can be reviewed in Broring et al. (2017) research study. In design perspective, these dis-connected interfaces add complexity for future IoT based product and service design. To tackle this complexity, UX can be used as a tool in holistic approach. Traditionally, multiple data points are generated on different devices consisting of different interfaces. A single platform gathers all these data points from different sources. For example, an IoT solution at a oil refinery industry might aggregate data from the oil machine, petrol, and workshop. The end-user expects a simple yet informative visualization on their dashboard which may be accessed via phone, tablet or computer system. In the oil refinery case, the product manager who monitors the factory would like to see working speed of oil machine. IoT solution should be capable enough to handle the diverse and distinct layers. Hence, the UX design becomes more complex when addressing all the hidden and visible factors available in an IoT ecosystem.

One of the methods to solve the previously stated challenges is to provide clear visualization of sensor data and processed information. According to Ware in Keller and Tergan (2005), the “power of a visualization comes from the fact that it is possible to have a far more complex concept structure represented externally in a visual and verbal working memories”. Furthermore, the cognitive load used by the human brain to understand the textual or verbal information could be reduced. Visualizations enhance the processing ability of human brain by depicting abstract relationships between visualized elements and may serve as a basis for externalized cognition, as implemented by Keller and Tergan (2005). However, computer scientists referred information visualization as “the use of computer-supported, interactive, visual representation of abstract non-physically based data to amplify cognition” from Sears and Jacko (2009).

2.2.2 Design issues of IoT

The chapter : *Real world design constraints* from Holler (2014) book briefly describes the design challenges in IoT ecosystem. They are broadly divided into three sections, namely technical design constraints, data representation and visualization, and interaction and remote control. The derived insights were related to data representation, such as unavailability of standard forms to represent data, demand of homogeneous visual interfaces, and inefficient storage methods. The practitioners and researchers from Krco et al. (2014) research have put an effort to ensure a common understanding of the IoT architecture design by assigning a common framework. This solution was proposed to comply the different requirements of different application domains belonging to a single IoT system. This limited interoperability issue further impeded the development of IoT system.

Different use cases were discussed by Montori et al. (2017), Ratan Vatsa and Singh (2015) showing a wide range of possibilities and complexity of IoT. To name a few, smart cities and smart environments include applications to monitor air quality, watering, and easy navigation. Further on, smart grid monitors the water networks and the usage of electricity. However, traffic monitoring is covered in smart transportation and logistics. All these smart projects are interconnected to each other and thus, sharing data across all the platforms. The efficiency and reliability of IoT technologies can be improved by creating better awareness of the systems. For example, Curry et al. (2018b), has narrated the impact of IoT data and its analysis on user behaviour model. The figure 2.3 (adapted from the same paper) also explains the improvement in user awareness level based on targeted information delivery. The paper further talked about the importance of engaging users by delivering actionable information. A similar approach was followed in the thesis during concept creation and analysis phase. Recent studies in-

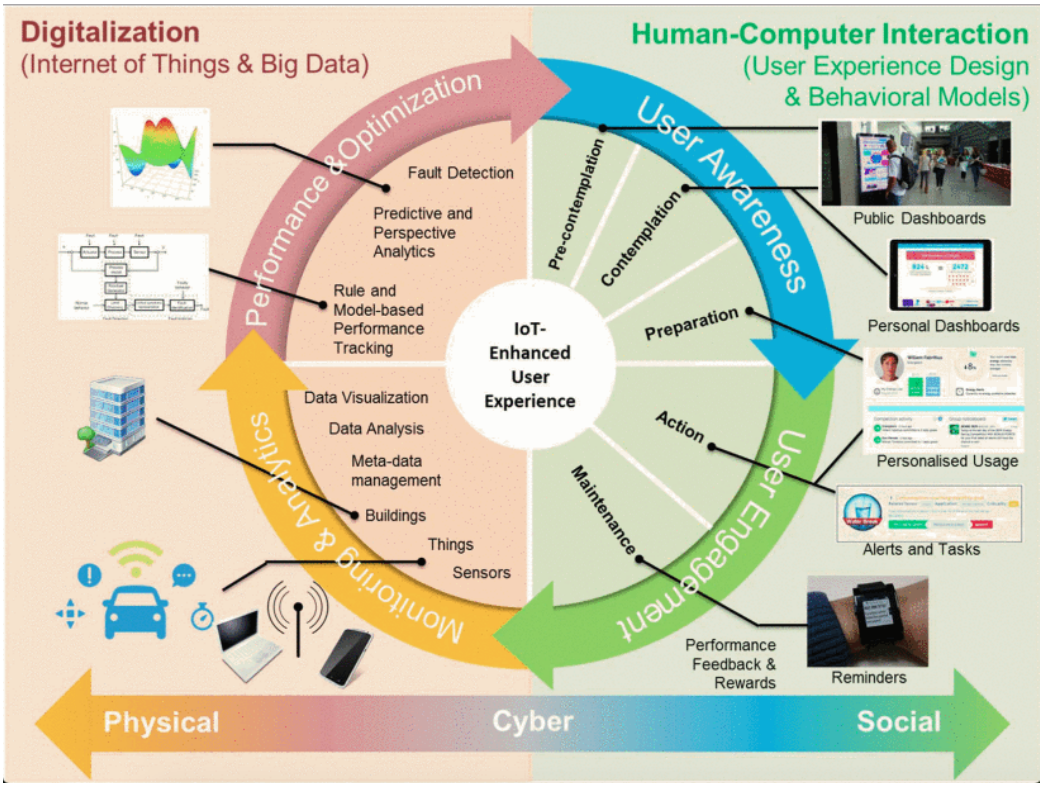

Figure 2.3: IoT enhanced user experience model

cluding Laha and Bowman (2012b) research have shown value of immersive virtual reality in the visualization of scientific and volumetric data. Moreover, Patrick Milliais, Simon, and Ryan kelly in Millais et al. (2018) study found that there is no overall task-workload difference between traditional visualization and immersive visualization, but there are differences in the accuracy and depth of insights that users gain. The study further investigated the influence of virtual reality on users' method of exploring data and gaining insights. The impact on users' experience and understanding of data inside the unreal world as compared to 2D visualization was also considered. As a result, participants who used virtual reality as a visualization tool rated their performance workload as lower (corresponding to increased feelings of success and satisfaction), compared with participants in 2D conditions, as also explained in Millais et al. (2018) study.

Primarily, researchers started using visualization as a supportive tool to explore large data set. Though the effectiveness of desktop visualization can be enhanced by providing facility and freedom to explore multi-dimensional data. This also relates to the two main attributes of big data which are abstraction and high dimensional data. The visualization is a bridge between the quantitative content of the data and human intuition, and this is an essential component of the scientific path from data into knowledge and understanding, as referred in Sharma et al. (2015) paper. A powerful visualization help to find attributes that would have not been found otherwise. Moreover, it allows understanding of both low-scale features and large-scale data, and learn how the data was gathered. A very famous Visual Information-seeking mantra from Shneiderman (1996) goes like "Overview first, zoom and filter, then details on demand". With the change of speed in every technology, the users are no longer satisfied with static visualization. They are inclined more towards finding new ways of interacting with the data and gaining more insights. Immersive data visualization is one of the new and effective ways to analyze data. Donalek (2017) and Kabil et al. (2018), are a few examples showcasing the possibility of effective data representation in 3D environment as compared to 2D.

A more natural and quicker method of exploring large data sets could be VR's wider field of view and increased spatial dimension as suggested by a few data visualization researchers. It could also add value to the gathered analysis of scientific data. However, as an exceptional case study, Lange et al. (2006) tried to drill down different concerns related to the visual data displayed in different environments and focused on how humans perceived more information in virtual reality environment as compared to 2D flat screen. The research examined how VR performs vs 2D when it comes to pointing out relative positions of objects. As a result of this study, participants were comfortable in completing their tasks using virtual reality as compared to 2D desktop. According to the author from Ware (2012) research, it is still an open question if VR has the potential to improve data visualization, especially in air traffic control situation. However, the main difference between 2D and 3D visualization is that 3D suggests a range of depth cues and perspective in the user interface as proposed by the same study. In addition, Gračanin (2018) stated that VR based user interface and visualization are used to evaluate IoT computing applications and further helps to test various IoT configurations while interacting with the VR space.

2.3 Immersive technology

An immersive virtual reality environment gives one a sense of being physically present in a non-physical world. The term virtual reality (VR) is defined as a medium composed of interactive computer simulations that sense the participants position and actions providing synthetic feedback to one or more senses, giving the feeling of immersed or being present in the simulation, as per Craig et al. (2009) study. Tools like Head Mounted Display (HMD) and a few other alternatives are used to create the illusion of being present in an unreal world. Beyond entertainment, VR has successfully deployed in various industries and used for applications like oil and gas exploration, scientific visualization, architecture, flight simulation, therapy, military training, engineering analysis, and design review as highlighted in Jerald and Jason (2015). Instead of creating an immersive environment, interacting with the system that involves real world image is also possible, this falls into the category of augmented reality. This technology can be applied in similar industries but for specific tasks like maintenance of complex systems, and visualizing data on top of real object. The mixed reality is where the virtual and real world fuses together seamlessly. Though immersive feeling can be provided by 360 photography and video, it still lacks the good experience which is otherwise offered by VR. Their development and outcome experience differs fundamentally.

2.3.1 Existing applications

Total immersive virtual reality is appropriate for applications like phobia therapy, medical or military training, and entertainment industry as proved in the study written by Doug A.Bowman (2007). Specifically for these types of applications, user requires high sense of fidelity - visual, auditory, and other sensory cues that matches closely to the real world experience. The creators of VR experience aim to provide realistic experience to the user by duplicating similar features inside VR world. This is achieved by focusing on two main attributes, namely Presence and Immersion. Mel slater in Doug A.Bowman (2007) research study defines immersion as the objective level of sensory fidelity a VR system provides whereas presence refers to a user's subjective psychological response to a VR system. Immersion is objective in nature, different systems can have different levels of immersion based on their purpose to fulfill. The level of immersion can be measured whereas presence is context-dependent. The sense of *being there* is dependent on the users' response and is related to the experience of the individual. Mel slater also proved that high-fidelity sensory stimuli helps to offer immersive VR by placing the user in the simulated environment and giving them realistic experience. There are also applications that does not make the user feel present but provide a simulated view of the real world without presence. The task efficiency might not depend on feeling of being there. In addition, the visualization might even be purposefully abstract, or unrealistic, to help the user understand the critical features of the space.

2.3.2 Benefits of immersion

The potential benefits of higher level of immersion other than providing a realistic experience are : spatial understanding and depth cues. The former aligns to be one of the most intuitive benefit and the latter means higher level of immersion. This impacts positively on applications such as design review, prototyping in virtual space, and digital data visualization. In addition, it decreases information clutter and thus, removes unwanted data. Two dimensional (2D) computer desktops are filled with overlapped icons, windows, controls and notifications. There have been several attempts to solve this issue by placing multiple monitors or virtual desktop. However, higher level of immersion might be able to decrease this information clutter with the combination of wide field of view (FOV) and high resolution, hence more comprehensible virtual environment which is suggested by Doug A.Bowman (2007). The higher level of immersion contribute to improved interaction task performance but lower level of immersion can also be helpful when the visualizations are less complex and more regular to interpret. The present use case of virtual reality in the society is briefly discussed by Kreis et al. (2018) which also helps to understand its role in the society. They also describe how the functionality and effectiveness has improved and will have an impact in future. Presently, practitioners in medical field use virtual reality to tackle different types of phobia with regular treatment. But the meaning for these new technologies in terms of UX is still unclear. With the rising applications and quick progress in the technology field, UX-centric process supports these fields to succeed. Since, the control is on people's satisfaction level and they will adapt to these new ways of living, it needs to be believable.

The wholesome virtual reality experience is created by combination of different elements of user experience, and cannot be created by modifying one or many user experience attribute. It goes beyond immersion and presence. According to Garner (2018), it includes flow, diegesis and fun which collectively illustrate the nature of VR experience.

Along with different components of VR experience, there arises interactive issues. Jared (2016) described that reality and location are two unique issues based on their dimensional model of VR experience. Here, "reality" refers to the scope covered by the material presented which either belongs to real world or is rendered content. The term "locomotion" refers to the possibility on how the user can physically move in the virtual environment. This led to the need of understanding user-experience in an immersive experience in order to ensure effective design systems and applications.

As mentioned earlier, immersion and presence are the hallmarks to provide real-world experience in simulated ambience. Yet another significant factor is interaction. Though immersion and presence are different at fundamental levels, they influence the interaction phase of VR. Identifying the ways people interact with VR is important as it might reveal potential use cases that are yet to be discovered.

Further on, Alam et al. (2017) discusses that the combination of partial immersive experience with IoT technology are implemented across variety of applications like web based AR application within IoT infrastructure, medical visualization, path planning, sensor-detection, and analysis. The virtual reality is also trying to change the working style of professionals. Companies provide collaborative virtual reality experience for teams to work together from remote places. They provide open-source systems that could be integrated with commercial VR headsets, such as Oculus Rift and HTC vive. So, by applying common tools the teams can create scalable VR environments. Presently, the market is booming with the successful fusion of real world and virtual objects through diverse real-time applications. Prototypical Virtual Environment of Things (VEoT), within an immersive 3D environment in which the user can explore the virtualized urban area and interact with the available smart objects through gestures and affordable VR devices is one proven example certainly researched in the Alessi et al. (2016) study. This analysis also provides the technique which could be used to prototype the low-fidelity VR environment.

2.4 Positioning of thesis

This section aims to describe the elements taken from each major topic, namely IoT, VR and UX to outline this thesis. From literature review section 2, it is seen that both IoT and VR technologies can be captured through the lens of user experience. According to Doug A.Bowman (2007), a good experience for VR is created with the combination of immersion, presence and interaction, as also mentioned in detail in the earlier section. However, Curry et al. (2018a) exhibits the possibility to qualitatively measure the users' understanding on virtual IoT concept . This is achieved by enhancing the user awareness level and maintaining the engagement level inside VR space. The below picture illustrates the core concepts used in this thesis. As the concepts are too wide, only suitable themes among the concepts are associated together. The goal of this research is to assist naive developers to learn IoT process. This is accomplished by visualizing the invisible data in virtual reality medium. In addition, the data was qualitatively gathered and analyzed to understand user point-of-view and the underlying reasons. All these pointers are incorporated together as data visualization in virtual reality. As a result, core focus of this research was formulated.

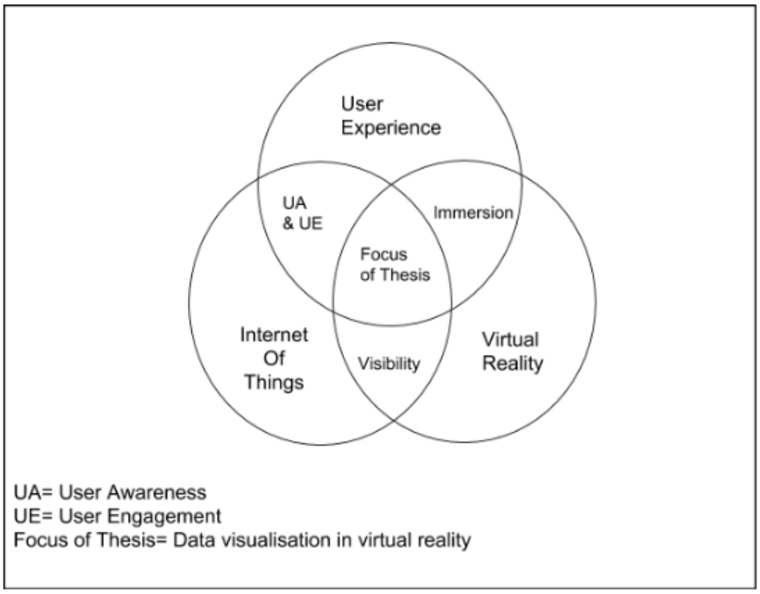

Figure 2.4: Positioning of thesis

Chapter 3

Methods

3.1 Data gathering requirements

This chapter includes the scientific research method required to execute the study. All the processes and approaches in this study are depicted in a step-by-step scheme. However, the tweaking of the concept prototype was an iterative arrangement. The goal here was achieved through literature study and expert interviews. This was inspired by Bergman et al. (2018) research. The authors describe the method to formulate empirical study, apply scientific method to conduct interviews, and analyze gathered qualitative data as shown in the figure 3.2. A similar approach for conducting interviews was utilized and the detailed description is available in the subsequent subsections. From the interviews, a number of issues were identified that correlated with the research from the literature study. Based on these findings, visualizing data and its flow were identified as suitable areas for further improvements.

In order to build and test this area, guidelines from Hevner (2004) research was implemented. He established seven guidelines to conduct, evaluate, and present design-science research. Specifically, a conceptual framework for information systems research both in behavioural-science and design-science paradigm. However, this thesis focuses only on the design-science paradigm which means addressing research through building and evaluating artifacts to meet the identified areas. Here, building the artifacts refers to prototyping. Further on, Carr (1997) defines prototype as instruments and prototyping as a process to build and refine a product in an iterative mode to meet end-users expectation. Hence, these guidelines were implemented during the prototyping phase.

Similarly in this thesis, Lo-Fi and Hi-Fi prototypes were developed in an iterative prototyping development approach. To develop these artifacts unreal engine for HTC Vive was utilized. In order to understand if the prototype was appropriate in learning IoT concepts effectively, testing with real users was conducted. This helped to recognize the relevancy of visualisation in VR and its influence on end-users.

Overall, a combination of these methods helped to execute the study in a fairly exploratory case-study style. In addition, considering the novelty and the nature of VR from industrial perspective, this study was guided by a qualitative approach. Comparatively speaking, quantitative methods are more suitable for objective goals than qualitative methods. The implementation was carried by gathering the requirements from stakeholders, followed by developing the prototype and testing the setup.

3.1.1 Theoretical overview of the methods

The design theories and implementation guidelines related to VR are thoroughly understood by studying the literature. The review process was followed under the guidelines of Kitchenham & Charters (2007). Nonetheless, it should be noted that these guidelines were not completely entrenched. The Systematic Literature Review (SLR) method was tweaked as the process was continued. To elaborate, this thesis only focused on the individual studies that contribute to a systematic review. These studies could be regarded as primary study. In order to attain full knowledge about the influence of VR visualization on IoT concepts, individual studies were carried out on topics, such as data in VR, 3D visualization, existing application of VR, and workplace environment. Due to the limited scope of thesis and focus, a systematic review in the form of a more comprehensive secondary study was not implemented. Although the SLR method is mostly applied in medical industry research, Kitchenham & Charters (2007) illustrates the guidelines for performing systematic literature review method in a software engineering field.

However, the insights collected in-process and the relevance with the thesis title promoted few changes. Precisely, only specifying the research question, identification of research, and selection of primary studies were the three stages that were finally applied. Moreover, the steps in these stages were followed only until it met the relevancy of thesis topic and the required level of knowledge to have an overview of all the concepts. To explain in detail, the initial search traced the most relevant information related to basics of VR. For example, the reading covered topics beginning from history of VR, basics of VR development, required level of immersion (for this particular prototype), interaction rules, techniques, visualizing data in VR, and existing prototyping tools available until September 2018. An assumption in regards to the validity of recently published papers and the market status of VR until 2018 from an online source was built during the search process.

In (Conceptual Background) section, a brief study about technologies that might be used as a medium of visualization tools were collated and noted. These technologies support extended reality, namely, augmented reality, virtual reality, mixed reality, and/or hybrid reality. The authorized scientific articles, books, credible websites, and related academic course study collectively contributed to this literature study

3.1.2 Best practice evaluation

Lavalle (2016) evaluates VR systems and experiences. This book describes thorough analysis on topics, such as suitable headsets, time required for a particular VR scene, required degree of field of view and so forth. Referring to some of the insights raised from the book, best practice approach were explored in this study followed by creating the high-fidelity prototype. Likewise, Hevner (2004) shared "best practice approach" as textual descriptive method while explaining the different processes that are implemented in a working system. Correspondingly, for this thesis, available software and VR prototyping techniques were inspected. This further includes VR designing tools, such as Tilt brush, Sketch, and Sketchbox that were manually pretested. During the learning phase, basic features were checked and applied to build a low-fidelity VR space. Moreover, augmented reality prototyping tools, such as Torch and Framer were also explored to push different boundaries.

The selection of a prototyping tool and platform relied on the experts' opinion, self hands-on experience while focusing on ease of use, degree of flexibility, consumption time, and lastly, online availability of required meshes and materials. A few ideas related to 360 degree and VR video were also discussed in the process. These techniques did not match the level of immersion required for the project and lacked its potential to provide interaction, thus, they were discarded at the initial stage. The figure 3.1 is a snippet of advantage and disadvantage analysis between AR and VR as a possible visualization medium.

3.1.3 Interview with stakeholders

Interviews were conducted with professionals within a VR development community in Finland and Sweden. The pre-requirement for connecting with experts was their association with the IoT and VR industry. People with

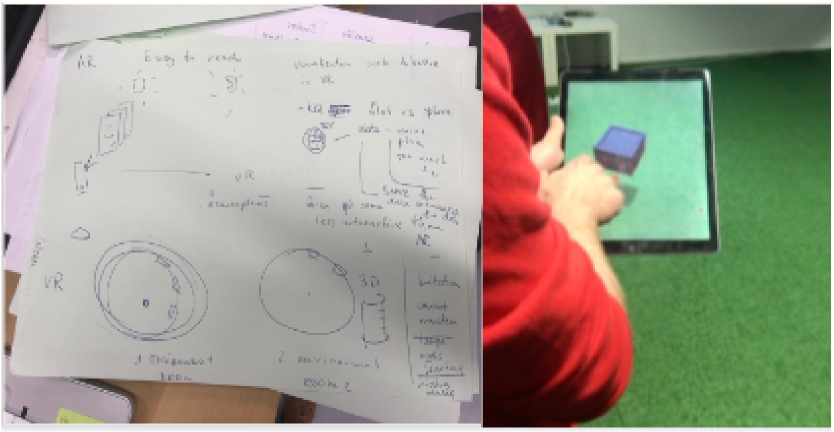

Figure 3.1: Advantage and disadvantage of immersive technologies

sheer knowledge were removed, because that would not help to deeply understand the technology. These interviews enabled the extraction of current market scene on VR-work related environments, projects related to visualizing data in VR, general challenges, and opportunities. As a result, experts from both small and large companies were added to the list.

From academic perspective, the overall planning was followed in regards to the method applied in Bergman and Johansson (2017). This research method follows a qualitative approach where companies were invited, interviewed and their recordings were transcribed to form conclusions. In this thesis, pilot interviews were organized to refine the interview questions. Nonetheless, Bergman's target audience differs from the current research study. The interview instrument in the Bergman's research was customized for companies, whereas, in this research the target stakeholders were developers and experts from different fields, this infers more user centric than product centric. However, the process followed in both the research studies as shown in figure 3.2, clearly describes the step-by-step scheme. Broadly speaking, this scheme is divided into planning, conducting and analyzing data. In order to attain knowledge on user pain points and needs, in-depth interviews were organized with IoT application developers. Further, the “Three Boxes” method from Hall (2013) was practiced to structure the interview questions in three broad parts: introduction, body and conclusion. The questions were tuned with respondent profile, as shown in Appendix A.1.

User needs - interview

Once the participants were selected, an interview was organized via skype and in-person (if agreed). The data was collected by applying a semi-structured

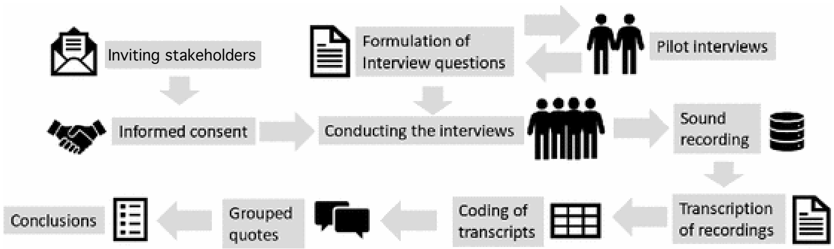

Figure 3.2: Overview of the method applied for interviews- Adpated from Bergman and Johansson (2017)

format. The interview questions were constructed in prior to the actual interview and later the respondents had the freedom to choose the order. This granted some space to explore the topics in a flexible manner. In addition, it allowed the possibility to have follow-up questions and sessions. The interview was planned in correspondence to the method as described earlier. The user segment required for the experiment covered IoT application developers working in environment similar to medium-sized startups. The interview question and answer sessions were mainly focused on understanding work issues that arise during the development cycle. Their voices collectively contributed to pick one of the available core issues, that also sounded feasible for the scope of this research. The product manager, ERP system developer, and IoT application developer were few discrete profiles among all the interviewees. A quick apprehension on these interviews are summarized in Appendix A.2 and in figure 3.3.

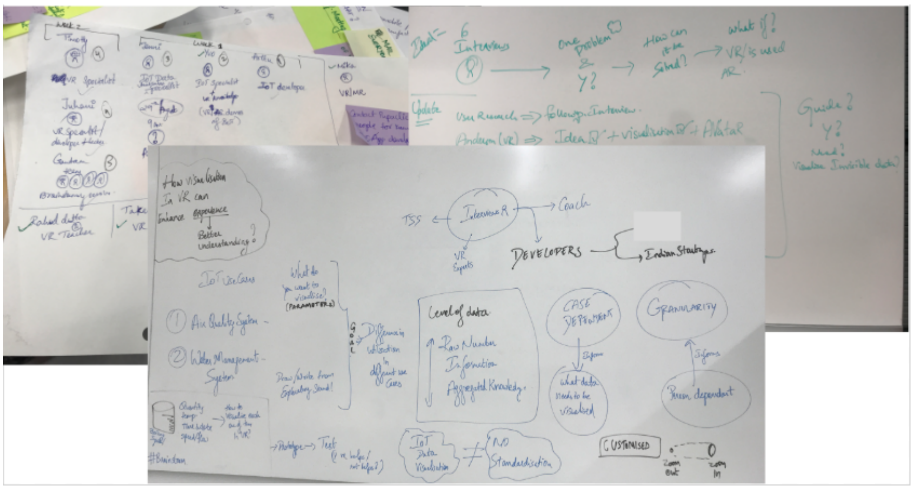

Figure 3.3: Snapshot of interview planning

Experts interview

The VR industry is growing at a greater speed and in broad directions. The experts from the VR community were interviewed to understand the ongoing collaboration between IoT and VR technologies, concept creation for VR prototype, and current practices to design VR application. In addition, the main goals were to familiarize with the established ways of a VR design cycle and understand the possibilities of virtual reality in enterprise solutions. This research could also act as an opportunity for networking companies, to explore the impact of new technologies and product benefits related to internet of things. To gain more knowledge about different fields and applications related to extended reality, specialists from disparate areas were also interviewed. One of the interviewee's was an IoT data visualization expert who specializes in understanding IoT data and creating appealing dashboards.

3.1.4 Preliminary analysis

Data was gathered and coded into transcripts utilizing online and offline solutions. The qualitative data was further separated into an orderly fashion using post-it notes. They were grouped on the basis of a similar pattern. In qualitative research, two main data analysis methods according to Bergman and Johansson (2017), are *generation of theory* and *confirmation of theory.* Since the aim of the analysis was to explore different possibilities related to UX, IoT and VR fields, the *confirmation of theory* method was chosen. This method allowed to find the evidence and support for a predefined hypothesis. A small sneak peek can be observed in figure 3.4.

Key information from literature study and interviews were gathered on real-time board (which is a web-page platform) and analyzed via post-it notes. This scanning helped to review the core concepts, challenges, and opportunities that sounded relevant and feasible for the prototype. The data source were associated together by the principles learned from literature section 2, the industry's outlook (AppendixA.2), and difficulties of developers (AppendixA.2). This helped to formulate the core topic of the prototype.

In regards to the analysis of data gathered after prototype test, Hevner (2004) guidelines were referred. The influence of the prototype can be rigorously indicated by well-executed descriptive evaluation method as supported by Hevner. Since detailed scenarios for the VR prototype were constructed to exhibit it's utility, descriptive method was applied. After gathering data from the user tests, qualitative approach was applied to analyze the data. Hence, conclusions were drawn from the insights constructed during the analysis process.

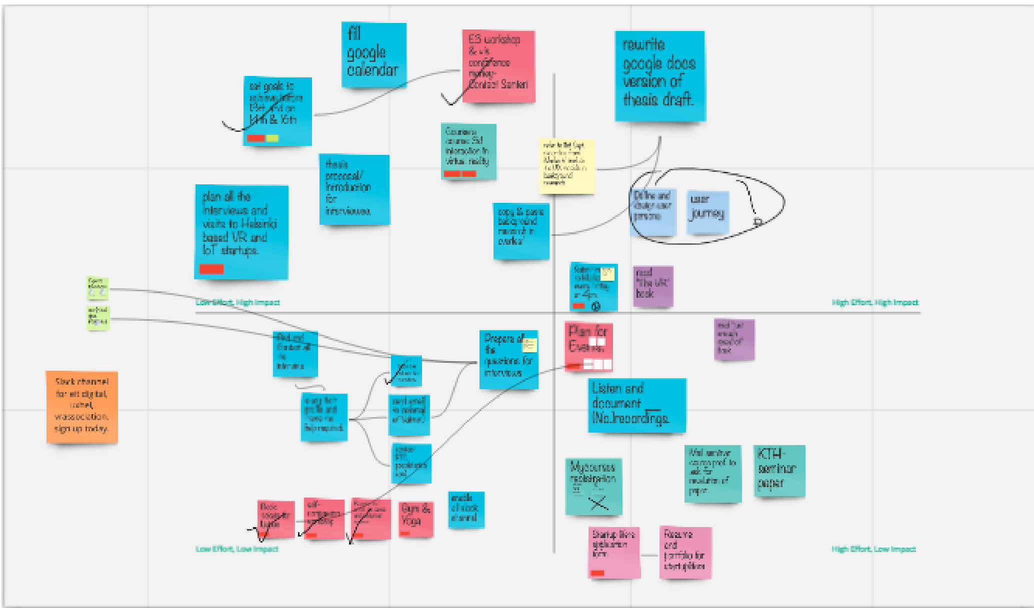

Figure 3.4: Snapshot of analysis of stakeholder interview

3.2 Prototype implementation

To evaluate the presumption explained in previous section 3.1, a single scenario was selected from several IoT based applications available in health industry. This section represents the design iterations and development process of constructing a VR prototype. The iterations were based on feedback received from pilot users and domain experts accumulated in the period of several prototype tests. This approach includes concept creation, sketching, Lo-Fi prototyping, and other technical settings required for running a VR prototype. The main focus of this implementation procedure was to get real time feedback on 3D visualizations and to evaluate how it enlightens one's knowledge.

For the scheme of this prototype, a single-way data gathering route of an indoor air quality measuring system was tested. The prototype was built with the support of Mixed Reality (MR) Hub which is a group of researchers situated in the University of Helsinki. The MR Hub provides a platform service which is known as MRS Studio. The platform enables non-programmers to get started with 3D modelling and customize VR environment. Based on the concept and elements created in Sketch subsection 3.2.2, the prototype was further developed and reiterated with pilot users.

Software and apparatus used

The software used to project 3D space was SteamVR running on Microsoft windows operating system. The prototype was developed on Unreal Engine 4th version. In addition, Gamebar from Microsoft was used to capture videos, screen-shots on 2D desktop. These clips actually captured the in-space of virtual environment which was also projected on 2D desktop.

The HTC Vive developed by HTC and Valve Corporation was utilized as VR headset for the prototype. The Vive controllers consist of four buttons including a trackpad, grip buttons, and triggers. The controllers can be used for six hours once charged in plenty. The controllers can target to any point within *room scale* with the help of a tracking system. The HTC Vive headset, along with SteamVR provides this tracking system. This allows the user to move free and interact with the VR space. The input sources for VR space could be through video, data, and bluetooth.

3.2.1 Concept creation

The concept of visualizing the system components and its flow addressed diverse key points during the process. The lessons from Lavalle (2016) were considered while ideating the concept for VR environment. The IoT system is a collection of networks, devices, and digital machines at numerous different level. In order to design a simplified version of this system, theoretical background and revelation from developers were analyzed. During the literature study, three case studies were highlighted, namely, IoT smart water management system, air traffic management system and indoor air quality (IAQ) system. The figure 3.5 is a snapshot of flow of IoT process with positive and negative points of every component.

Based on available resources, experts guide and time constraint, IAQ system was considered for prototype. As shown in the picture 3.6, first all the components were modelled and then exported to virtual space. Initially, the main components were placed inside the VR space. The order of the components reflected the order from the blueprint. After fixing the positions of the components, 3D texts were added. The location of 3D texts were adjusted with reference to corresponding 3D model. Followed by, arrows and other minor models to complete the flow.

This allowed to consider the key features of the system from start, explore the relationship between the components and identify the role of data at each phase. All these features were dotted down as requirements list (as shown in figure 3.7) and placed in a flowchart to match with the functions of corresponding components. For instance, indoor air sensors holds many

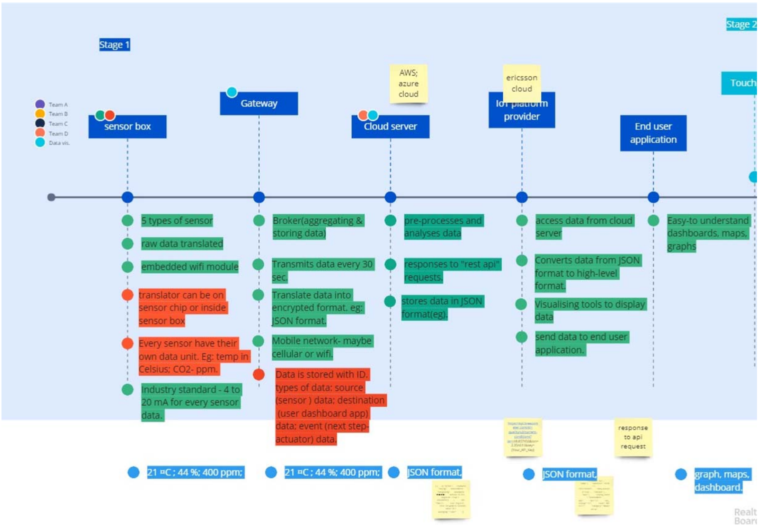

Figure 3.5: Flow of IoT context

sensors together like temperature sensor, humidity sensor, carbon dioxide (CO2) levels, dissolving organic compounds, measure utilization rate, and background noise. For this specific prototype, we considered only the four key indoor environmental parameters, namely relative temperature and humidity, particulate matter (PM 2.5), volatile organic compounds (VOCs), and CO2. The data regarding four key parameters were referred from the article - Sensirion Inc (2017) and their ideal values to indicate good air quality was considered from the Finnish Institute of Occupational Health (FIOH), so as to follow the industry standards.

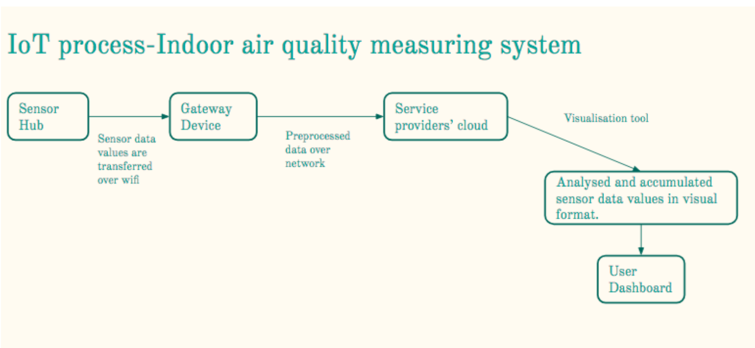

Figure 3.6: Basic level of data flow in the respective IoT system

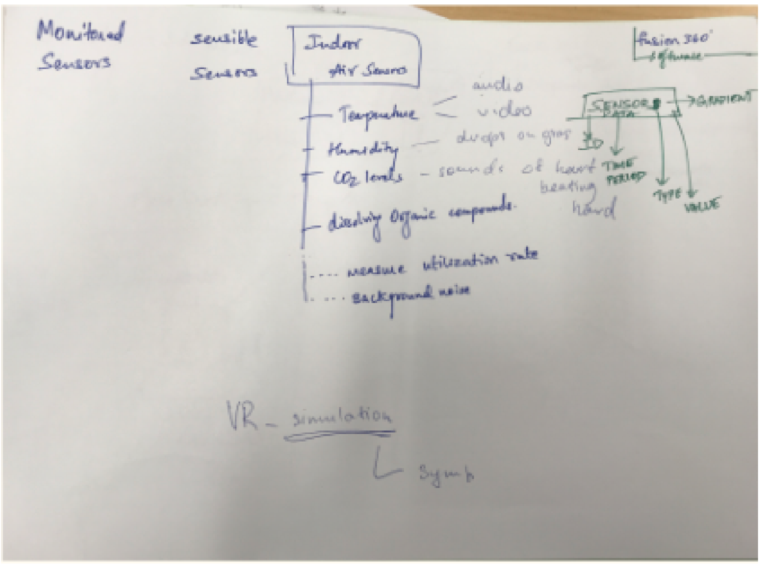

Figure 3.7: Requirement list for the prototype content

3.2.2 Sketch

After analyzing individually, all the components and phases were sketched on paper. The aim was to find optimal visual for 3D space as compared to existing 2D visual model. The drawings reflected similar ideas on the functionality of every element when visualized on 2D/3D plane but they were discrete in their visuals. After the most desirable 3D models were chosen, a storyboard was gradually created on VR sketch sheets McCurley (2016). Key indicators for the actual content were emphasized during the process. A snapshot is shown in figure 3.8.

After the storyboard creation, the IoT system was unfolded in a low-level proof-of-concept prototype. This process also sparked the capabilities of unreal engine as compared to Unity technologies. One of the benefits, of using unreal engine is its potential to render photo realistic images in real time and blueprint features. This helped to create interactions within the engine platform, which allowed advance optimization for VR and inculcate rapid prototyping method. Running 3D environments are more intuitive way than rendering 2D images as they were more interactive and accessible. For developers, unreal engine stands for game-developing engine whereas for designers, it is a tool to design and create interfaces.

In regard to the prototype, the 3D texts were added to introduce the sections and key functions behind the components. The intention was also to provide navigation using low level indicator if the user felt lost inside the

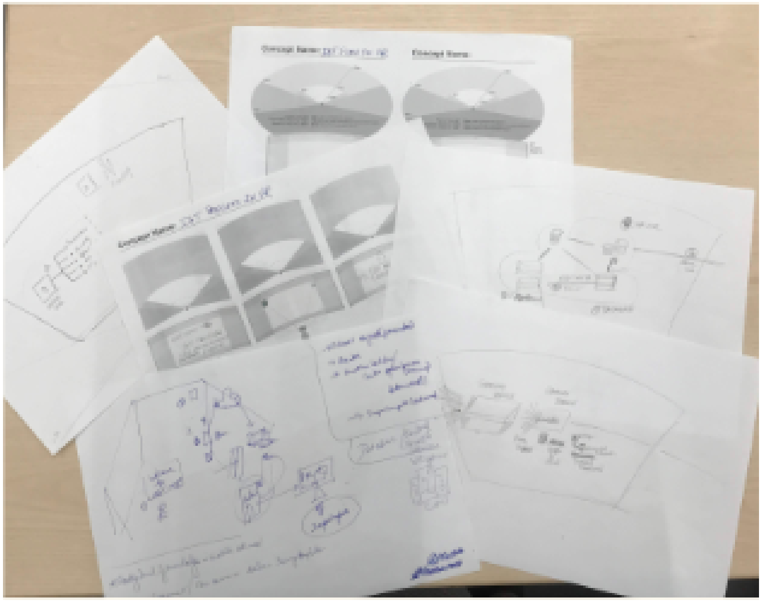

Figure 3.8: VR sketch sheets

space. Reducing the usage of texts and replacing them with images or other visuals were mostly prioritized.

In terms of visuals, the two design concepts that were highlighted during the sketch timeline were skeuomorphic design and abstract design. The former refers to interface design reflecting real world objects, whereas the latter refers to unrecognizable patterns and forms. These unrecognizable visual design allows degree of freedom, flexibility, unlike the visuals that adhere to real world reference. Both design concepts hold positive and negative points and yet are best suited when used in balance. For this research, the aim was to visualize real world IoT process to teach new trainees. However, the advantages of 3D space allowed to explore and strive for maintaining a balance between skeuomorphic design and abstract design.

The process was activated by understanding the existing forms of the components. Digital icons, visuals from current extended reality solutions, and physical products were some sources for inspiration. Finally, visuals of each parameter was sketched on paper, as part of low-fidelity prototype. Although, few questions were raised and answered during the process. For instance, the unit of each parameter was different. Even if the granularity of data informs the user type, user needs case dependant data to exactly know what to visualize. Moreover, The data which is either universal in every case or customized to specific situation could be visualized. The finalized visuals were further modelled in digital format. Some were perfect fit for the process and some required more iterations. A very few visual models were also removed to clutter the unnecessary information. For instance, the user dashboard section did not require modification, as it represented the skeuomorphic design. The sensor hub section, CO2 sensor, cloud service provider section were few examples that required more iteration. In detail, sensor hub model did not justify the value of physical device and thus, it was changed as shown in figure 3.9. However, the CO2 model was designed in abstract form. The visual model was influenced by the underlying concept of gas fumes. The subsequent sections explain the entire process of visualizing data in digital format and the reasons behind reiterations.

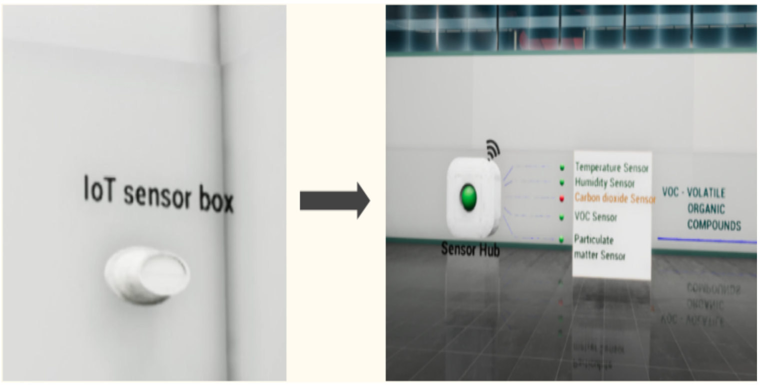

Figure 3.9: Visual : Sensor hub section

3.2.3 3D meshes and environment

The Unreal Engine-4 provides support to import 3D models in specific formats and create meshes for the same. Mostly, the required mesh actors and environments were modelled using Sketchup, by Google.

One of the main points to consider when modelling complex 3D structures is to identify the basic shapes and combining these shapes to form a complex one. For example, the structure of *cloud* was one of the most challenging mesh, as seen in Figure 3.10, to create.

Hence, four spheres were combined on top of one another and blended at the edges. The white material with grey border was added to give look and feel of cloud. Yet another option was to import a similar mesh in the space and assemble each individual static mesh structure (asset) by changing the geometric values in “Detail panel”, available inside the software.

The background setup is a space representing the interior of a advance technology building. The corridors on three different floors were also designed

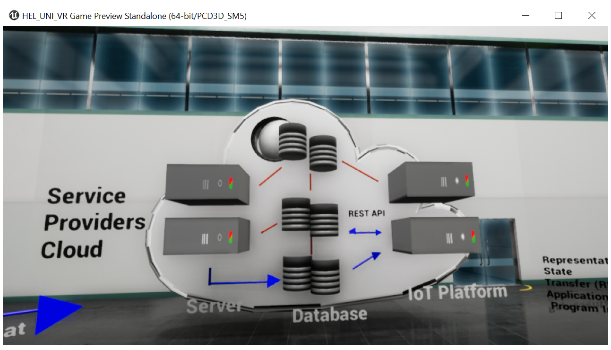

Figure 3.10: Visual : Cloud structure

to give the user a feeling of standing inside the building. The static mesh actors present in the space are glass windows, whiteboard with pens and duster, all system components.

The project already had placed all the direct lights in main areas of the hall. The actors were placed from *"place mode"* button. They are modified by using scale, transform, rotational tools. The scene is developed with high fidelity rendering of models and thus, meshes did not require external optimization work. Every time, a new mesh is imported in the project, it is pre-processed and optimized to maintain the same visual quality. This is implemented by reducing the number of polygons, also called as decimation method.

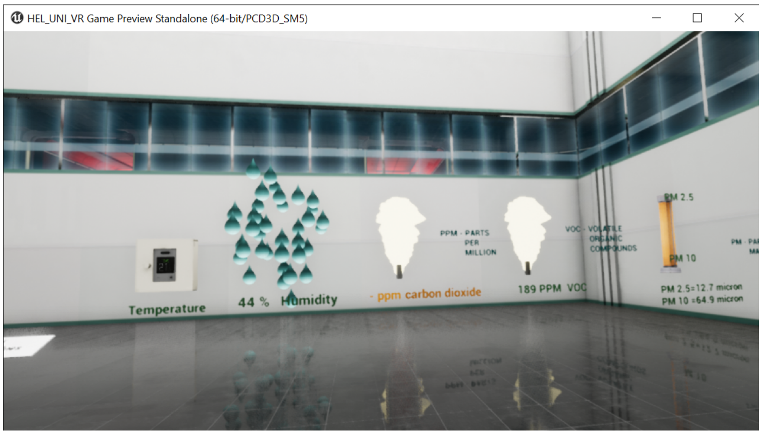

Figure 3.11: 3D Meshes : Sensor data values

As shown in the figure 3.11, 3D meshes were placed in the space, followed by the arrows to help users navigate through the process, and then finally, texts were added. Furthermore, referring to renderings of other models, few materials were created within the project. These materials were mainly focused on presenting the actors as technical and realistic as possible, referring to the real world devices.

3.2.4 Interaction

One of the key aspects for good user experience within virtual space is interaction. The main goal of this project was to validate the impact of immersive visualization and thus, imparting interaction was essential in a way that user would feel natural and intuitive. For usability test, less information and less interactivity task were considered to avoid bombarding the user with stack of information, new space, and new technology. To reflect on scope of the prototype, natural interactions were included - considering the fact that it makes use of the usual everyday skills of human lives. It is a tough trade-off to keep the experience plausible and usable at the same time.

The prototype was built by keeping track of more passive interactions and less active interactions. For instance, user could not choose any objects inside the space but when the user looked around, the headset responded the same way. The user would do what he/she would naturally do to look around instead of looking for Sci-Fi type of interaction or even any other real-world interaction, such as scrolling up the space view.

Yet another interaction, as show in the picture 3.12, was to use paint brush to draw and write text inside virtual space. Fortunately, this feature exists with HTC Vive controllers. Similarly, it is essential to provide an unambiguous and clear interface to the end users. They must know what is happening at any time and must get immediate feedback from the interface.

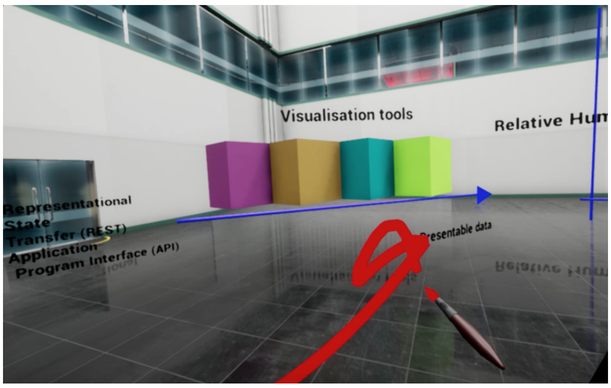

Figure 3.12: Virtual brush in VR space

3.2.5 Movement and orientation

The indoor room design allows users to move around freely. The users were given the flexibility to move in any direction, zoom in-out of any (presented) object. The principle of six degree of freedom was considered during the development process. This allowed the users to feel present in the unreal world, giving a full 360-degree experience. The HTC Vive is featured with infrared cameras, enabling the expansion of physical area in virtual world and reflecting user movements from physical world as his own character in synthetic world. The extended reality technology is rising towards delivering more realistic experience and a totally immersive package.

"Teleporting" is a technical term known within the virtual world. It refers to moving inside virtual space instead of physically walking to that spot. The VR room is a setup to synchronize the physical area with virtual area before running any program. This helps the user move within the boundary of real-world area and still explore the virtual area which are often bigger than the former size. The users find it helpful to move around freely in virtual world while standing at one place in real world. To teleport to a spot, one needs to mentally measure an approximate distance and use the controller (in case of HTC Vive) to place the laser pointer at that spot. This is a bit tricky for the first-time users and might need some time to outdo.

In this prototype, the vision was to impart the feeling of safe, natural and real when the user walks through the IoT system setup. This vision was accomplished by setting all the components in a linear format, enabling the user to navigate in a single direction. The intention was also to feel oriented with the system. Initially, all the components were placed on inner walls of the building, just like in any art museum. The components were shifted to the center to avoid the hassle of covering the perimeter of this room. The pilot users suggested this shift, as they felt like the components were placed too far away and a lot of empty space was wasted. All the iterations are summarized in the table 3.1.

Prototype	VR Interface	Reason
Prototype 1	• The setup was designed as a big hall with the starting point inside a room. • Component models were placed. Avatar (narrator) was added. • Video screen was added.	• To give the user a feeling of standing inside a room. • The placement of component models reflected the blueprint architecture. • To explain the IoT process in brief and to maintain user-engagement level with the VR space, Avatar was added.
Prototype 2	• Avatar was removed and so, audio was also removed. • Text were added. Light animation was added.	• To focus only on visualization aspect, audio was removed. The easy, less-effort and more effective method to explain the sections was via text. • To guide the user through VR space without audio, light was a suitable option.
Prototype 3	• Text and component models were synchronized and placed close-by. • Light animation was removed and arrows were added. Video screen was removed. • Few models are rearranged and colors, shapes, and depth are further enhanced.	• Reflecting on pilot tests, the models were placed closer in a semi-circular way. Due to time constraint, light animation could not be implemented and thus, it was replaced by static arrows. • To remove information clutter and keep the prototype focused, the video screen was removed.

Table 3.1: Prototype Iteration

3.3 Experiment setup

The following section describes the test setup that was utilized for both pilot test and actual test rounds. After developing the prototype, initially, the pilot user study was organized before the actual user testing. The aim was to receive feedback on 3D visualization and on the overall experience. The potential users and domain experts from MR Hub shared their affirmations about the satisfaction of understanding the visuals. Also, the dilemmas that were encountered while navigating through space. The raised issues covered topics, such as users could follow the process, if visuals conveyed the intended meaning, and comprehend the data flow, and so on. These were answered during the pilot test process.

(a) Room setup

(b) VR setup

Figure 3.13: Test environment

Based on the target user profile and VR equipment, the MR Hub was a suitable place for usability testing. The testing environment was preferred to be silent and spacious, to enable clear recording of users voice. The MR Hub is situated in the University of Helsinki and this helped to recruit participants on site. Only one participant was allowed to test the prototype at a time. The images 3.13a and 3.13b showcase the real-world room setup and in-screen VR setup.

3.3.1 Participants

During the development stage, ten pilot users tested the prototype and shared their feedback. Pilot tests were helpful in addressing a few issues that were unknown during the first iteration of system design. The actual test participants were five students from different academic backgrounds. All of them

Metrics	User-1	User-2	User-3	User-4	User-5
Demographics	Male	Female	Female	Male	Male
Age range (years)	35-44	25-35	25-35	25-35	25-35
Location	University of Helsinki	University of Helsinki	Aalto University	Aalto University	University of Helsinki
Work life	He is working as a social science researcher.	She is pursuing masters in Physics.	She is a recent graduate from data science track.	He is studying electrical and communicatio n networks masters.	He is completing his diploma on psychology of religion.

Figure 3.14: Participants profile : part 1

had a basic understanding of web development. The target group for usability testing were university students. Some students were invited via email and some were handpicked while passing by the tested area.

In the survey form, participants were informed about the scope of research and the way their data will be handled. Before starting the test, users were verbally informed that they were free to discontinue the experiment at anytime and they could remove the headset at anytime. Since there was a possibility that users might feel some sort of discomfort and motion sickness while using the virtual reality set (including controller and headset).

Surprisingly, every participant spent more time (10-15 minutes) within the virtual space than the usual time span of 5-7 minutes. Three participants out of five had experienced VR previously but had poor knowledge on IoT application development.

All participants were requested to speak-out loud while performing the given two interactive tasks in the VR environment. Both the activities include drawing the data flow using controllers but from two different starting positions. The users operated the virtual brush via controller in virtual space. They were permitted to point the virtual brush in any direction and start drawing. However, the application did not support erasing the drawings if they wished to clean the space.

The participants were video recorded through the desktop-screen and a camera phone, including the gestures and voice feedback. During the test, the participants were eager to share their suggestions regarding future improvements and excited to use the virtual brush to draw the same. The valuable feedback was collected during the post-interview.

Experience Metrics	User-1	User-2	User-3	User-4	User-5
Programming	He has developed basic webpage using Javascript and Python.	She has been practicing programming on and off, developed fe websites running on Java, HTML, and CSS.	She has studied and practiced programming for past 6 years with a background in computer science.	He has studied and practice programming for past 7 years.	He attains basic website coding skills. He has used HTML and CSS for the same.
(VR) virtual reality	He never tried VR application before but was curious to try this prototype.	She has never fully experienced VR before this prototype. She has come across extended reality booths in Tech-events, but until participating in this test, had never used VR controllers.	She has played basic games in extended reality setups, including augmented reality headset. She said that due to novelty of the technology, she didn't get proper exposure to it yet but being a developer, she is very interested and looking forward to develop VR applications.	He has played VR based games in conferences and exhibitions. He has also watched few 360 videos on mobile application.	He has built a basic unity based VR game and played few games at company stalls.
IoT (Internet of Things) knowledge	No knowledge on IoT application development	She confirms to have poor knowledge on IoT development.	She had no formal training in IoT application development and measures the level as very poor.	He possess limited amount of knowledge on IoT application development process.	Very poor knowledge on IoT application development.

Figure 3.15: Participants profile : part 2

3.3.2 Procedure

The prototype was examined in three phases which includes introduction and reflection survey, usability testing and post interview. The aim of this study was to validate if users comprehend the showcased visualization, like visual clues and forms, and perceive its intended meaning, in this case, flow of data. Given three tasks were the basis for success criteria, figure 3.16. Each task demanded focus and system-interaction capability from the users.

Phase 1: The purpose of phase one was to introduce the user to the test-setup, collect background information and test basic knowledge on the Internet of Things (IoT) and indoor air quality systems.

Phase 2: User experienced virtual reality demo. During that process, user had to complete three tasks given by the interviewer. First, the users were given a chance to browse through the VR prototype. During this time, they were asked to speak out loud as they experience the prototype. After browsing through the prototype, and while still wearing the VR headset, the users were asked with a series of questions about the visualizations in the prototype.

- Task 1: Talk out aloud- explaining what the user was seeing,feeling and/or understanding.
- Task 2: Show the data flow from sensor hub to gateway device.
- Task 3: Show the data flow from gateway device to user's dashboard.

Phase 3: Users filled the survey questions. These survey questions were framed to help participants reflect on their experience of using the VR prototype and to test how the prototype contributed to their understanding of data flow in a typical IoT System. The post-interview questions were a series of questions focusing on the visualization part of the prototype.

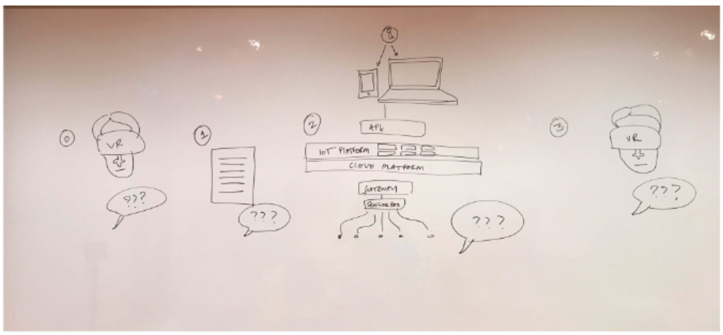

Figure 3.16: Rough sketch of the plan

Chapter 4

Result and Analysis

4.1 Overview

Users were invited to test the setup presented in virtual reality and qualitative data was collected to evaluate their understanding of the setup. The insights gathered from a user data analysis were helpful in answering the following research questions :

- How visualization in virtual reality help to understand the flow of (IoT sensor) data?
  - What is the level of immersion required to understand (IoT sensor) data?
  - What are the advantages and disadvantages of VR based visualization?

Summary of recorded user test
Users were recorded both on the desktop screen and on a mobile camera during the test. The collected data included user interaction with the system, hand gestures, and voice feedback.
User interview summary
Semi-structured interviews were conducted after the prototype testing. The questions asked were open ended. The interview also included comments on the learning experience, observations, and levels of understanding for each user.
Questionnaire findings summary
Survey questions were employed to provide the users a way to reflect on their experience. The questions also included a scale to measure spatial movement, engagement, and motivation level. This scale was ranked based on a 5-point

Likert scale. In general, the value of 1 referred to negative side and 5 corresponded to positive side on the measuring scale. In addition, the questions were divided in three groups. The first section was aimed at introducing the IoT development system to the users; especially, the indoor air quality measuring system. The second and third sections were focused on collecting user feedback on the prototype.

Qualitative Data

Note taking often provides more in-depth background and reminds an observer about the events. The descriptions about the field notes must be accurate and without bias, as mentioned by Sutton and Austin (2015). In this research, qualitative data was gathered in four different ways: desktop-screen recording, user recordings, open-ended interview questions, and survey questions. These methods captured users' actions, reasons behind the decisions taken during the tests, and audio documentation of their comments. The collected data could help understand the user behavior inside VR, the way the users' handle the controllers and the VR headset in a real world. Further on, the interviewee's comments were transcribed word for word without any bias, by the interviewer.

The above data collection strategy ensured the process to be easy, to understand user experience without relying on sheer memory recollections. The purpose of writing the users' comments and observations was to collect concrete and real data directly from the user instead of rephrasing reflections based on an interviewer's perspective. Yet another goal to note down recorded observations was to review users' satisfaction level with visualization and find more insights for evaluation. Transcribed user comments and vocal feedback collected during post-interview slot were also utilized for analysis. Along with this, participants were encouraged to speak loud their thoughts and their understanding of the system when present inside the virtual space.

4.2 Summary of findings

Summary of recorded user test

As a part of task, participants were asked to draw the data flow of the indoor air quality monitoring system. The drawings were made using the virtual brush in virtual space. All drawings were saved in the form of screen-shots from the desktop-screen recording. The screen-shots served all the possible technical details needed for further analysis.

For further analysis, the drawings were re-sketched onto paper. All the drawings were matched with the actual system flow. Even though each participant had a different way of tracing the path, everyone managed to depict the data flow accurately. Everyone had their own style of writing and drawing. They tried to explain the flow of sensor data value of the IAQ system using these illustrations. A few users were comfortable with writing just the first letter of the components. One of the users was also eager to draw the data visualization chart while the rest preferred to draw icons.

One obvious limitation of desktop screen recording was the incapability to record the users' themselves. Although the actions from the virtual space were successfully recorded. To evaluate how the users perceived the visualization, recording their physical reactions was important. Thus, they were video-taped while performing the tests. The participants were informed in prior that the recording was purely for research purposes and will not be used anywhere else without consent. The virtual reality goggles hid distractions from the real world, and the user could focus only within the virtual space. As a matter of fact, only the user interaction within a virtual world and their perception of 3D visualization was important for this study. For every test user, 2D desktop screen recording was initially activated using windows software and later on manually monitored by the experimenter.

The most common behavior observed in the recording

- Most of them were seeking some feedback, either from the VR system or via human-to-human communication.
- Initially, most found it difficult to operate VR controllers but eventually were comfortable with it.
- Most were hesitant and confused while looking at a *Cloud server* visual.
- Two of the users had blurred vision while looking through the VR headset at certain angle.
- Users preferred to speak the whole word and either draw an icon or write the first letter representing the same object.
- Most completed the task to draw the data flow by via virtual brush.

The visuals that were easy to comprehend

- *Sensor hub* section- consist all the sensor names and connectivity module.

- All the texts visualized in this prototype were perspicuous and readable.
- Most of the users grasped *visualization tool* section, except one user who was confused with the visual of *abstract boxes*.
- *User dashboard* section was lucid for all the users.

The visuals that were challenging to comprehend

- *QR code* invoked different meanings and purpose of use to every user.
- *Cloud server* platform was too overwhelming and complex for the users.
- The intention behind *sensor data value* visualization was not described clearly to the users.
- The *Converted data* section was clear as a whole step but individual components like *QR code* and *Wi-Fi* were unclear to the users.

User interview summary

This section includes five qualitative user interviews and their reflections on visualization in virtual space. The participants belonged to different educational backgrounds and had different levels of experience both with virtual reality and IoT application development. The interview was organized in an open-ended semi-structured format with seven questions to effectively collect users' reflection. Some extra time was also allowed at the end to discuss points that perhaps were missed in the previous session.

The interview questions are mentioned below

- How was your experience in VR space?
- How satisfied or dissatisfied are you with this visualization?
- What is more confusing or annoying about this visualization?
- Which (other) kinds of information would likely be in VR space?
- What were you expecting?
- Explain how would you visualize data flow? Did visualization help you understand the flow?
- Is there anything else you would like to add as a final note?

Participant feedback

User-1

He stated that VR prototype was an interesting experience. He acknowledged the importance of visualizing flow of data in an IoT-based system after the prototype. He also agreed that visualization of data helped him understand the flow. He pretty much understood the process but was not sure about the credibility of the process. He mentioned, *"I cannot say if it is a good or bad representation as I do not know how the actual system functions in real world! But I understood what the system was doing through the visualization of it"*.

For user-1, the most confusing visuals were the boxes present under the *visualization tool* section. This was difficult for the user to understand the intention behind those boxes. *"I quite did not get the point of having abstract boxes under the text"*, said User-1, *"...something explicit. For example,... graph representation or specifically what kind of visualization ... not clear if the graph(after visualization tool) was actual representation of graph or just a sample to show this is how it will be!! "*.

User-1 felt the environment was clear and consistent. He complimented the overall experience as pleasant and understandable. *"Both 3D objects and images definitely helped to get a gist of it!"*, stated user-1. He also pointed out that some information was missing when it came to detailed function of every section. For instance, it would have been better to explicitly explain the conversion of data from JSON format to visual format. However, as observed with other participants, user-1 was not really curious about every section and their working nor was he sure if the (presented) system was doing the job as it was supposed to do.

In the final task, user-1 could see the whole flow by standing at one

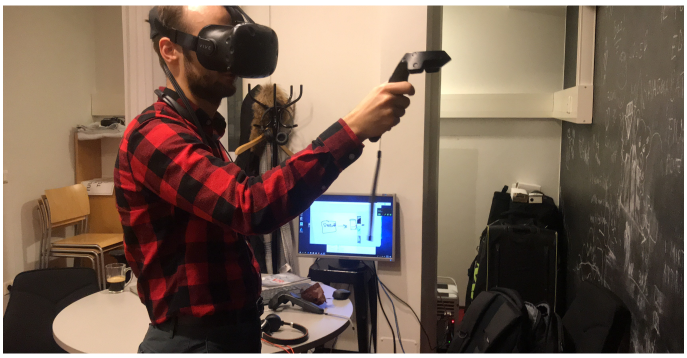

Figure 4.1: User-1 performing task-3

position through the umbrella view and draw the same using virtual brush. He was not sure what was the exact text represented at *gateway device* section but he was certain that some processing happened at gateway device and thus, he included *processing icon* in his schematic representation. The image 4.1 is a desktop screen-shot of him performing the third task.

User-2

The most time spent during the prototype for user-2 was while learning controllers and teleport activity. This was clearly due to newness of the experience. *"It was okay! It took time to get used to it, how do I teleport myself but it was okay after sometime."*, said user-2. So, she did eventually get the flow. For a first-time user, the information to remember and process at first stroke was substantially high.

She felt that combination of text and images helped her to understand the process well. *"Visual cues helped to understand data. Colour and text were supportive to understand the difference. Visualization helped to understand the flow but I was not sure how the system should actually work"*, said user-2.

According to her, all the information related to data transfer and flow was available in the visualization, she further suggested - *"... show the patterns formed by the data points at highest or lowest value. It could be part of further research,"* she said, *"But as the data is travelling at regular interval of time, .. data is already extracted to find the reason, so it is already available in this system!"*

Well, this shows user's motivation, engagement and level of interest both in IoT application development and in virtual reality. She referred the data as points and data flow as signals travelling through the system, these signals are decoded to analyze which signals means what and presented on dashboard. The figure 4.2 is a snapshot of the participant performing task-2.

Figure 4.2: User-2 performing task-2

The concept of visualized data inside virtual reality was appealing to user-2 for its ability to explain the process of indoor air quality monitoring system and how data transfers from one section to another. In final task, user-2 used first letters (of the corresponding word) to explain every section of the process and arrows to show the flow. She could not remember a lot of detail and thus, she used the 3D virtual system as a reference model and completed her task.

User-3

The most satisfying aspect of the prototype for user-3 was the overall understanding of the process. *"Even though, I did not have any knowledge about IoT but still I got the basic idea how data flows, what kind of process goes as raw data through visualization ..."*, she said. The main technical points the user brought up were related to some troubles caused during the testing, namely: operating controllers with different features was difficult for both first time and regular users, and abstract visuals without text triggered different interpretations from participants. She also mentioned that the easier way to understand the flow would be to actually see the flow in motion from one section to another. Although, motion in VR was acknowledged during the development process but could not be executed due to time and resource constraints.

The user-3 highlighted that titles for every section inside VR space was helpful. In addition, displaying real time examples would give more information to the user like show how exactly is the data processed or converted. In terms of prototype, she said, *"... some parts can be detailed or well-represented. For example, ... what does this picture mean? maybe you could use some device and place data values on it, to make it easy to understand"*. She could easily connect the present VR space with the functions of an actual IoT system from the real world. This also infers that the user comprehended the working logic of the system shown in the prototype. She highlighted the stage at which the data was in raw format and then later converted to visual format for end users. Mainly, to let the users understand and show the difference between the status of sensors (indicated with green-red color).

In final task, user-3 was quite eager to use the controller to draw with the virtual brush. She drew icons and wrote texts to support her explanation, as seen in figure 4.3. She fully understood the data flow of an indoor air quality monitoring system and explained the same with all the available details. The *visualization part* was very obvious and simple to comprehend for user-3. However, the *Cloud server section* was too big and seemed too complex, hence, she suggested to show the motion of data flowing through the cloud.

Figure 4.3: User-3 performing task-3

She had a pleasant and fun experience, and with a developer role, she is looking forward to learn more in virtual reality. She stated *"Flowchart will be good. One good thing about VR is to have the flexibility of zoom in and out, teleport far and near as required. For example, you can hide pre-processing part and if I want to see the inner logic then I can press a button and see how it actually works!!"*.

User-4

His first statements in the interview were, *" It felt quite surreal, like transported to another world. It was quite exciting!!"*. It was one of the most insightful interview among others and also ignited few future possible improvements that could help developers learn through 3D visualization. Regarding the visualization, he understood the overall process, and appreciated the way the visual models were represented. He added, *"I am quite satisfied about the visualization in it ... learn about how the data flow works and what happens in a IoT system,this would work great! ... this is an easy way for them to see without going into the essential details... a very very intuitive way to learn "how the system works?". For a system level overview, this works perfectly."*

Though, he was not sure about specific parts of sensor data value section, he was convinced about its role in the process and found it useful. He claimed that he has no imagination skill and he cannot visualize when he reads a text or someone describes a visual to him. However, he was asked to explain how he would visualize the data flow and if he would prefer doing something entirely different or something similar. His response opened up new avenues for visualized data in 3D space. He suggested,

"For anyone with technical background... streams of data, like, 010101,...

a pipe or something, like data flowing through pipe... (before gateway) the data is in bits and then it is in JSON file...different formats so people understand that here (before gateway) it was unprocessed data and then it is processed data."

The most surprising takeaway for user-4 was realizing that there are so many components in between the sections. In addition, to understand the real time concepts. For example, sensor data are not processed just once but many times at different phases in an IoT process. Before this prototype, user-4 considered an IoT application development process to be collection of sensors which sends some data and then somebody in the cloud processes the data. He added, *"... multitude of sensors, and they send unprocessed data to the gateway device ... the pre-processing of data and convert it into some sort of meaningful data and send it to the cloud for further processing... visualization tools where it further fetches the data to user dashboard."* He

Figure 4.4: User-4 performing task-3

also described that this method was quite fast, as he could *"walk back and forward with it and look at it, to read the text and understand it"*, compared to traditional method which would have taken notably more time. Here, by traditional method, user-4 is referring to reading books, memorizing by sitting at one place.

In final task, user-4 was excited to explain his acquirement from the prototype and draw using the virtual brush. A snapshot is shown in figure 4.4. He mentioned that being a person who cannot imagine things in his own head, the prototype helped him a lot. It provided the ability to see all the devices and data in physical form. This format felt very easy and intuitive for the user. He completed the task by writing first letter of the word related to every section (inside rectangular boxes). The letters were followed by arrows and abbreviations to complete the logical process.

User-5

User-5 explained from different angles why he felt this as a different experience than compared to other. He understood the starting point of data flow and even further, he suggested that *air particles* must be visualized before sensors. The reason was to show that sensors were collecting the data of these air particles and in addition, to make the process feel more intuitive and real.

He verbally explained the task-2, supported with virtual drawing in the space. *"If I understood correctly, Here is the sensor, a particle come in sensor hub, sensors basically convert the information into information/data and send that to the next thing which is through Wi-Fi, I guess, probably."*, he said.

He was interested in every detail and did not want to miss out on the obvious things. Even without prior knowledge on different types of data formats, he related the technical terms, the one represented in one of the sections, for example, *JSON and HTML* as some readable format. He was mindful that the texts shown were the converted data formats and will be send to *Cloud server* section. He was also playing inside the space and having fun, a short snippet was captured when the user was showing the data flow from sensor hub to gateway device, he said, *"Lets send a blipp this way!!..haha.."*, figure 4.5.

User-5 was excited about the prospect of learning through virtual reality and felt pleasant by the end of the prototype. In the final task, he was eager to explain the data flow as he was confident about his mastery on the IoT development process. He wrote texts and drew images of every module. He also suggested, yet another module, to add control section at the end of the

Figure 4.5: User-5 performing task-2

process. Basically, replicating the *control system* from real world, to give more freedom to the developers to interact and control the whole system. He said, *"Yayyy!!... then maybe the next level with interface you could have some controls over.. whatever you could control ...maybe over the air or humidity."*

Questionnaire summary

The aim of questionnaire was to collect users' reflection on their VR experience and post-understanding of the IoT system. Out of five users, the ratio of student and male participants was higher than female and working participants respectively. Three users out of five measured their level of knowledge on IoT application development as poor knowledge and have had previous experience with virtual reality, figure 4.6.

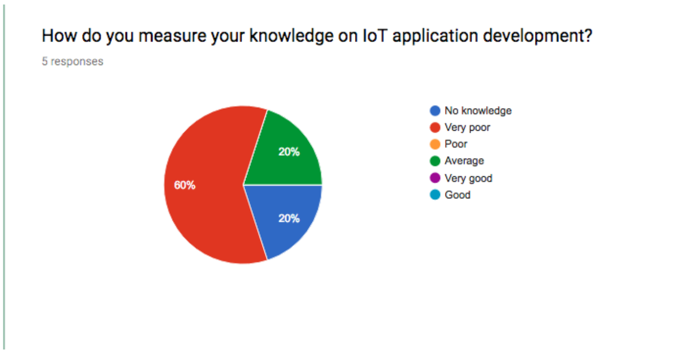

Figure 4.6: Participants knowledge on IoT concept

Initially, all the users were skeptical and neutral to the fact that visualization of data helps to articulate data flow. The user-2 was still neutral after the prototype test. However, user-4 and user-5 strongly agreed on the positive impact of visualization and the rest fairly agreed to this statement. In the figure 4.7, all the colors representing positive answers are noticed.

Few questions also led to different meanings. For example, a question from Spatial section, *"Did you feel the environment was significant or insignificant?"* faced this dilemma. Here, *one* means most significant and *five* means *insignificant*. Users were unclear if the word *significant* meant importance or irrelevant and hence, demanded a more clear explanation from interviewer. A quick snapshot is attached in figure 4.8. Thus, the first learning relates to the framing of appropriate questions.
On contrast, the question : *"How uniform the data can be received from the sensors?"* was uncertain to all the participants but yet after the prototype they confirmed about the non-linearity of sensor data values. A quick

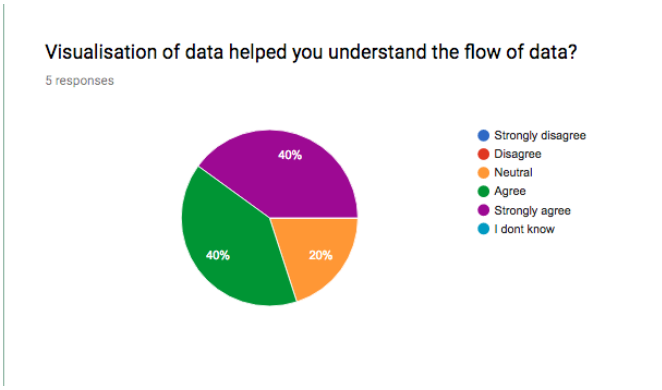

Figure 4.7: Positive impact of visualization

reference can be found in figure 4.9. The statistics showcase the users understanding after the prototype test.

All the participants reported that they felt free in the virtual space - figure 4.10. More precisely, the freedom to walk around, look at the objects from various angles, and ability to interact contributed to feeling of free. They also had a clear understanding of the environment except user-3, who found it a bit confusing. The user-4 and user-5 explicitly shared their feeling of fully immersion within the virtual space as compared to the other users. The participants also confirmed that they had a concrete mental image of the spatial environment even after the prototype test, as seen in figure 4.11. This shows that visualization with spatial understanding help to retain for long time. In overview, survey reflects that users had some clear vision by the end of the test. Most of the users were engaged inside VR, exploring the 3D visuals to understand the entire process of data. As a part of reflection,

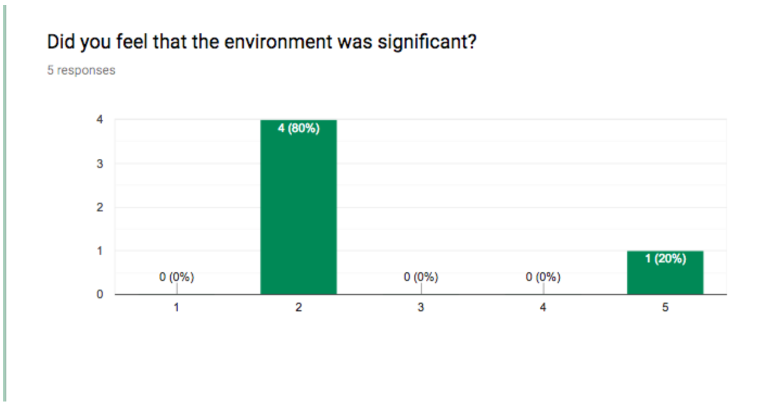

Figure 4.8: Spatial section : Significant vs Insignificant

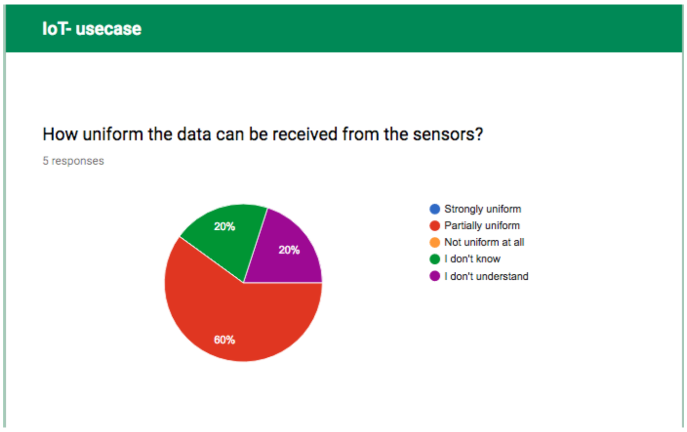

Figure 4.9: IoT concept validation

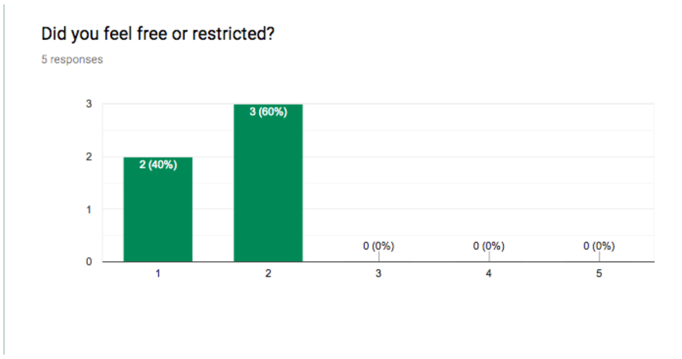

Figure 4.10: Motivation section : Free vs Restricted

all the users presented a positive feedback about the importance of seeing visuals of data to understand the whole process. If visualized properly, it helps to understand the minute details of devices and their process.

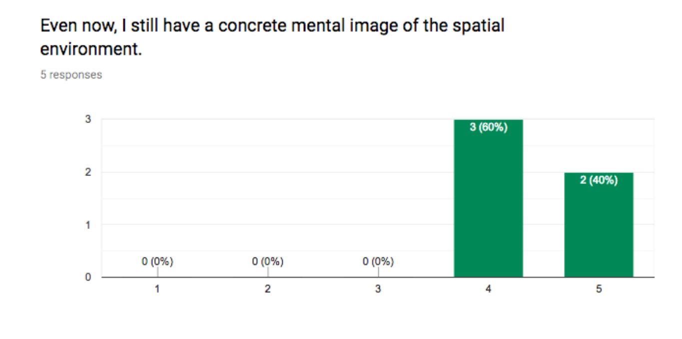

Figure 4.11: Spatial understanding helps to retain data

Chapter 5

Discussion

This chapter discuss the results obtained from the user prototype test in conjunction with the interpretations from literature review in order to answer all the three research questions considered in table 1.1 introduction section. The following subsections also supports the answers by acknowledging the findings from other researchers in the same field. This also includes personal reflections and learnings from this research project. The section 5.1 : shares how visualization in virtual reality helps to comprehend the IoT sensor data flow. Further on, the section 5.2 provides evidence from literature study on the required level of immersion for training purposes. The section 5.3 unfolds the positive and negative findings of prototype test. This section basically illustrates the advantages and disadvantages that needs to be considered while designing the VR experience for an industrial use case. Finally, since the goal of the prototype test was to address different verticals at the same time, thus the interview questions were organized and framed based on their validity and background research. These verticals were associated to areas like data visualization, spatial understanding and motivation level, user awareness related to internet of things, virtual reality, and user experience.

5.1 3D visualization helps understanding of data

As seen in result section, developer's insight highlights the importance of visualization. This also provides supporting evidence for the research question : How visualization in virtual reality help to understand the flow of (IoT sensor) data? The obtained result confirmed that visualizing data helps the user to understand the flow, the process of the IoT system and gives more ideas to effectively build this system in future. All the aspects corresponding to the understanding of data through 3D visualization are consolidated in the successive text.

Specifically, in regard to 3D visuals, only 3D text or only visual objects did not fully support the user to perceive the overall working of the system. Instead, the combination of both text and images with predefined purpose formed a better story for the user. This was explicitly demonstrated by the users during the prototype test. As also mentioned earlier in analysis section, user needs introduction either in the form of title or side note and then 3D models to see the actual components. However, Millais et al. (2018) also shares similar findings from their study. According to them, the participants proclaimed lesser inaccurate insights of visualizations in 3D space. They revealed an elevated feeling of success and satisfaction in VR space as compared to the 2D environment. Moreover, the authors in the same research compiled the aftermath to be an increased level of attention and accuracy as a result of satisfaction and success.

In relation to showing data flow in 3D space, pondering on direction, data formats, timestamp, location and other parameters that are relevant to the system flow are crucial. Displaying only the direction of data-flowing through the system for a user who wants to learn at a very basic level might be enough to reach the goal. Whereas, linear direction might not be enough for users, such as developers who are much more interested in learning about the system in deep level of coding. In addition, the sensor data value should be showcased with some more detailed information in every step of the process and should be revealed when the user asks for it.

The flexibility to reveal *more information* should be given to users while interacting with the virtual world. This was also discussed in previous research by Shneiderman (1996) who defined the visual information seeking mantra. He introduced seven task list, namely overview, zoom, filter, details-on demand, relate, history, and extract. According to him, these provide users with immediate information and enables safe environment where users rapidly explore the information in self-controlled system. Subsequently, some of these approaches require novel data structures, high-resolution color displays to be completely effective. Moreover, in this thesis users understood the *flow of sensor data value* by walking through the whole system but showing the actual flow inside VR would be much more easier and effectual. This demands motion within VR space which provides effective technique to share data with the users. Hence, data flow in 3D space requires consideration from all the vertical aspects to provide conclusive experience and information.

In regards to cognition perspective, learning in 3D environment might also reduce cognitive load on users brain. Keller and Tergan (2005) described that visualization might be utilized as a fixing tool for problems occurring due to the restrictions of time and capacity in working memory. In addition, Cox (1995) proved that visualization extend individual's competence in dealing with complex cognitive task requirements. Consequently, this was also observed during the prototype test in this thesis, confirming the effectiveness of visualization in 3D space. Although, the memory of each individual plays a huge role in their learning curve. On one hand, user-1 and user-2 had an overall understanding of the VR prototype but they could not name every component while sharing feedback after the test. They used desktop images to point the components and reconfirm the text. On the other hand, user-3, user-4 and user-5 were confident about knowing each component even after removing the headset. Hence, visuals in 3D space should be clearly tailored according to each individual learning style.

In qualitative interview section, framing questions was one of the challenges. However, questions for the survey were articulated under the guidance of Lombard et al. (2015) measuring scale which focuses on presence, spatial understanding, motivational, and engagement levels. Although, interviewees were mentally prepared to spend 30 minutes for research but accessing all the answers from the user at once was difficult. Asking open-ended questions and recording them to utilize it in future during the analysis phase proved to be logical. However, noting users feedback was a good option but recording the audio and video was better, as the expressions, quotes, and key insights were captured all at once. Yet another important learning was to let experts and potential users try the prototype and be a part of the prototype plan. This is similar as trial-error method, where the concept is prototyped, experts review are received and the prototype is further modified.

Subsequently, understanding the concepts through visualization also helped the participants to reach a better level of retention. This when applied in industry background, can also benefit companies who utilize VR in employees training programme. They do not have to retrain all the employees all the time and still provide a unique experience. Traditionally, users watch something passively and not participate entirely or do something hands-on. With the capabilities of VR, they can go through the motion in a safe and controlled manner, as quoted by one of the experts interviewee. In addition, telecom companies who operate with IoT devices in diverse scenarios, such as irregular intervals of utilizing IoT devices within a certain period, or even products that get activated only when triggered can benefit from VR. Moreover, the visualization of invisible data could be challenging as it is dictated by the habit of IoT devices. Hence, visualizing these complex IoT sensor data within VR space will help users memorize the data flow and provide deep insights.

5.2 Required level of immersion

Based on the insights derived from the literature review, the prototype for this research was built in such a way to provide a partial immersive experience. In technical (hardware) description view, the full immersion is provided by six degree of freedom in the head mounted display feature. The partial immersion is provided by the lower degrees of freedom as compared to the former one. Overall, immersion is enabled with the conjunction of a rendering software and a display technology, as described by Doug A.Bowman (2007). One learning obtained from this research was, the immersion level should be tailored according to the goal of the application and how comfortable are the users in VR space. Doug A.Bowman also discusses the implementation of VR in phobia therapy, as one of the VR examples. According to him, the clinical psychologist as part of their therapy applies VR to treat patients dealing with the fear of height. Usually, the VR application takes the patient in a step by step routine. First, the patients are placed on a small heighted object while gradually increasing the height after every level. This application helps because of the illusion of being present in that space and yet having a strong feeling of standing at a height.

In addition, Slater (2018) paper elaborates the positive influence of the feeling of "being there" utilized in different scenarios. He argues that the feeling of presence and full immersion helps to learn concepts in a better and an effective way. The reason behind full immersion for learning application is the accessibility to depth cues that are required to understand and remember concepts. Subsequently, similar results were found by Laha and Bowman (2012a) where they enlighten the positive impacts of immersion for volume data visualization.

A key insight gathered through this research was that users, as in, developers were open to try new methods and techniques which are quick and effective. The user preferred 3D visualization, they acknowledged the concept of learning inside virtual reality, freedom to interact, and move around the static components that they might not be able to do in real world otherwise. One of the lessons learnt was that improper visual clues can lead to misunderstanding of the element in VR. Moreover, it might also create confusion between grabbable and ungrabbable objects. Thus, self-explanatory features will improve the user experience and make the user feel totally immersed in the space, as required for learning application.

Furthermore, Lee (2017) discussed similar points in his research. He mentioned that *"depth and object sizes in VR applications are helpful when defining a possible collision."* This statement also provides supporting answers to know the required level of immersion so as to understand the IoT sensor data in VR space. The study discusses findings similar to the prototype test results from this thesis. For instance, the participants confirmed that the VR environment was immersive both in qualitative interview and in the survey. Additionally, they claimed that they would prefer to have more interactions with the objects in future prototype. Henceforth, providing a partial immersive experience within VR space for learning and training is helpful.

5.3 Advantages and disadvantages

The qualitative analysis provided a list of positive and negative points associated to visualizing in virtual reality. The below summary highlights important topics parallel to 3D visual design, qualitative user test, and technical restrictions.

Summary of negative findings

Some of the negative points in regards to visualization in 3D space are highlighted in this subsection. At first glance, the abstract visuals were not clear to the users. They appreciated the visuals as presented but did not understand the purpose behind its presence. For example, user-1 could not pin down the reason for having boxes under the text *visualization tools* section. He stated that "even with just text - the message would have been conveyed, I do not understand the value of placing the boxes here!" And, user-4 was not clear with the placement of sensor data value visualization. He mentioned that *"... instead of user dashboard, why there were graphs, humidity and everything like other visualization tools part in middle?"* Some users perceived the same visuals as an example that would be displayed to the actual end-users, and a few others found it challenging to understand it's intended the purpose. The most unexpected result was users reaction on *sensor data value* visual. The abstract images of humidity, temperature, VOC, CO2, and PM2 level were developed in order to validate if users understood the context behind abstract images, as in, data value.

The *Quick Response (QR)* code visualization confused the users in terms of its functionality and actual role in the IAQ working system. Some users understood it as a format in which data is stored, and some took it as a tool from which they can access more information about the data. Henceforth, different interpretations were made on the same visual.

Yet another example was *Wi-Fi and Cellular* icon. The icon was very well visualized as referred to the real world image but confused the user on how they should be utilized, as in, its functionality. Except one user who brought up two different meanings of the same *Wi-Fi and Cellular* icon, everyone else understood the authentic purpose of showing a connectivity mode. The user-3 explained that this could either be used to show the connectivity mode or represent the data itself. She was confused and uncertain but motivated to explain different possibilities. Users also mentioned, they had to adjust their headset to see the visualizations clearly. There were few technical limitations that affected the virtual reality experience like user-3 stated that visualizations were seen clear from certain angle but unclear from few other angles. Initially, user-3 found it difficult to teleport inside VR space but was fine after practising twice or thrice. The users had to put extra effort imagining that data is flowing (in motion) from one point to another.

Clear visualization of *QR code* was also required and this could be achieved with the support of text and uniform colour, texture based on its purpose. Lack of more detailed information was found as an important next step towards making this learning guide more engaging. Filling the 3D space with information everywhere is not the intention but to maintain a balance. Users would like to learn what the title meant to further understand the meaning conveyed through the accompanied image. By understanding the system, users understood the flow of data in the presented (particular) system.

The users had to assume all the minute details to comprehend and process information. Instead a suitable technique would be to provide the users with the obvious details, to help them understand the *flow of data* easier and better. The users also got confused by difference in visual color, structure and size of the same visual object but located at different places. Even with the text *pre-processing data*, and visual 3D mesh *21 degree celsius to QR code*, users did not understand the conveyed meaning. This also affected the understanding of data flow but only related to its format, as in, the way data is processed, the format of data. However, it did not affect their grasp on *the direction of data flow*.

Most of the users were unsure on how the data is actually processing in cloud. Firstly, because of its complex structure and secondly, the way it is represented. Just arrows were not enough to highlight the direction, because it is difficult to understand the visuals at one-go. It would have been better to introduce the flow of data using animation or continuous loop running video. Users had to go back and forth between the components to understand the intended logic and relation between each section. This might have confused the users with the minute details of each component but might also have helped to relate the internal sections. The visualization presented in this VR prototype focused more on the working of IAQ system rather than highlighting the flow of data.

Yet another opportunity to improve this prototype is the need of properly framed survey questions. The users felt unclear about a few questions when read once. These questions were related to IoT development process and virtual reality experience. They needed an explicit explanation from interviewer to receive a better understanding. Humans always look for affirmation from some online source or other person. For instance, the users could not understand the meaning of *uniform* in survey question. They did not get the point of this word or what it actually meant in this context. Henceforth, there is a lot of space for improvements in this research.

Summary of positive findings

This subsection describes the few positive findings that were noticed during the research.

The first time users were excited and motivated to operate controllers. They recognized the technique to apply virtual paint brush within VR space in second trial. In regard to interpreting visuals, abstract visuals were clear for the participants to understand at some locations in VR but also received different interpretations from them at other spots. For example, the figure 5.1 representation between humidity and temperature was clear to all users. For instance, the user-5 recalled it as *"the visualization of sensor data, to see some patterns... "* The information hierarchy helped the user to follow the data and also made the experience simplified. The experience might have left negative impression on the users, if they have felt overwhelmed with overloaded information at the same time.

The users had a comprehensive view of the system and the flow of data

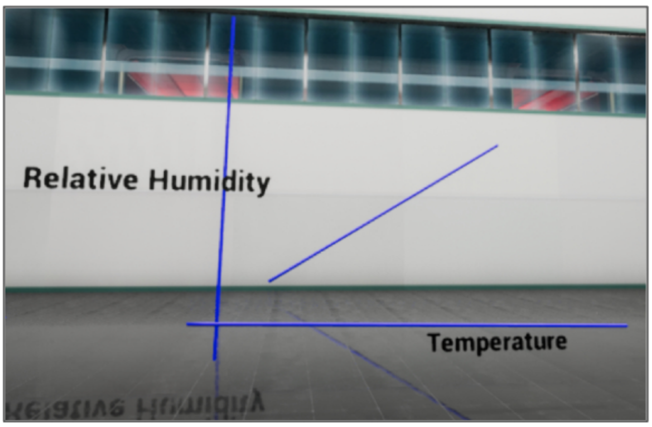

Figure 5.1: Abstract visual : Graph

across IoT based IAQ system. But to understand each and every component at one glance was a challenge. Being in a 3D space, the users utilized the freedom of moving around and inspecting the models based on their own preference. In addition, text at every section supported the user to recognize the 3D models, providing a gist. For instance, the graph visual successfully conveyed the relation between the x-axis and y-axis as shown in figure 5.1.

A graph was represented as an example to display the patterns formed between the processed data values. Moreover, the users were convinced by the 3D models which resonated with the real world images but took a bit more time with abstract images. The accompanying titles were useful as it introduced the sections to the users. The pilot users also commented that having some animation playing in a loop that would explain every step when the user is near to the model would be helpful.

In regard to natural interaction, the tools, such as whiteboard attached with pen and duster, and virtual brush were well accepted by all the pilot and actual users. Moreover, they tried to operate these tools similar to the tools in real-world. But, the actual functions in VR space limited the full utility of the tools. Thus, the positive point to noticed was how quickly users related the tools within and outside the VR space to the real world environment. However, it does require some improvements from the technical implementation perspective to make the users accessibility easy. They also mentioned the need for displaying the status of data, such as, raw data value, pre-processed data, and processed data, explicitly in the prototype. Moreover, experts interview emphasized on improving the experience of developers within VR space and integrate the development process in VR environment to improve the quality of the outcome. Hence, synchronization between components and overall flow is important. Thus, by following the above mentioned guidelines, it might help to build an effective 3D environment learning.

A few insights gained during the analysis phase was related to working in excel sheet vs. *Atlas.ti*. These insights were created while qualitatively analyzing the data. These are discussed below:

- One of the advantage of using “Atlas.ti” software over excel sheet to analyze data was the flexibility to see the video and code them at the same time. In addition, the possibility to take screen-shot from the video and tag them. The screen-shot could be the entire frame or just a section of the frame. This helped to gather evidences for further analysis.

- The technique of inspecting video data in “Atlas.ti” includes creating quotations and codes. Once the codes are created, these can be defined and tagged with simple "drag and drop" feature to other quotations available in the entire video.

- Operating on "Atlas.ti" is far better than running between excel sheets and videos. It saves a lot of time from jumping in between multiple windows to doing everything in a single software.

5.4 Personal learning

In the beginning, the scope of this research project was wide. This elicited the need of a strategy to stay focused and relevant in the context. Even though, rough strategy was created, it helped to keep a track of the project. Considering, it was not a linear process, few iterations were made with the progress. Also, a personal journal to keep track of my thoughts and findings during the whole process helped me store insightful information related to this study. The below section summarizes the learning acquired during the process:

Technical skills
This subsection describes the learning acquainted in VR design and development topic. Since, the thesis topic is a combination of three different areas of interest, namely IoT, VR, and UX. Previous experience supported to have some knowledge on user experience topic but virtual reality design and the way IoT system works were relatively new.

In the era of immersive 3D content design, the opportunity to experience the VR design and development process was fun and challenging. Initially, in the learning process, the role was to be an observer but was later realized that one needs to experience to know how it actually works. A few tricks and tips from experts were collected but they were not that effective until tried manually to design scenes within VR.

Sketching the scenes on VR sketch sheets helped a lot to bring the ideas into real life. This also helped to convey the ideas clearly to others and receive feedback. There were a few differences between sketches on paper prototype and the actual 3D visual in VR environment. In order to achieve the end-goal, one must think beyond the rectangle boxes while designing for VR space. This opens the option of illustrating models in and around the space as compared to 2D constraints.

The most necessary lesson to be aware was to consider the difference between creating novel experiences and replacing the usual UI elements. The designer must consider the distance between the content model and viewing position. They must try to create balance between these elements. Further on, developing VR using unreal engine helped me trigger the implementation process. The most effective way of developing VR prototype was to follow an iterative and rapid process.

Interpersonal and communication skill

Interpersonal skill can be interpreted as the personal skill to interact with the people within the same community or corporate unit. However, communication skills enable people to convey the message effectively in-person, public, meetings and/or writing emails.

Both the interpersonal and communication skills were assessed during the meetings with the concerned supervisor and advisor. Along with the supervisor meetings, even stakeholder interviews contributed in improving the communication skills. These meetings helped me recognize the areas that needed progress.

An effective communication is an inclusive package of asking questions, speaking, and listening. Since, questioning is one of the fundamental tool, it was important to frame the questions correctly. During the initial stages of the thesis, accessing answers and direction from the mentors was relatively easy. Although, later on, it was not that easy to extract direct answers as it dependent on how the questions were framed. In addition, notes were taken to highlight the important points and reflect on the takeways at the end of the meetings. Later, these worked as a part of speaking and listening practices.

Closed-end and open-end questions were asked during the meetings. They were applied depending on the requirement. For instance, closed-end questions helped to attain confirmation on the current knowledge and the latter helped to access more insights. Lastly, prior to the meetings, the conversations with the mentors' consent were recorded. This helped to pick up the recordings later in the process, if something was missed otherwise.

5.5 Limitations and future research

Certain challenges were derived from the results of literature review and empirical study. These challenges along with the suggestions related to future work are listed below:

This study covered only a linear process of IoT based indoor air quality (IAQ) system, due to the complex layers available in IoT systems. To an extent, the prototype concept was successful in explaining the whole process. But, as compared to the real-life scenario, there are many factors and developing stages which has a direct and a indirect effects on the execution of the system. Thus, in order to investigate further, the study could be expanded to the whole IoT ecosystem. Although illustrating the journey before and after IoT portal could be supplementary. This will motivate application developers to learn about the scenarios that might occur after developing the application in real time.

In context of VR development, though this study has shown that visualizing motion using static elements is possible, it still need some improvements. In order to create a yet more impactful visualization, animations to display data and its flow can also be considered for future work. Either the data points can be created as animated entity with the help of existing software or static data elements coupled with basic scripts can be developed as looping animations. Moreover, the need of fully immersive solution was highly noticed and one of the biggest challenge was navigation because there was no audio or instructions in VR prototype to guide the user. Anyhow, the visual clues with the help of motion or even navigation light could resolve the same issue. Let's consider, user are able to interact with the models and as they change any feature of the model, the effect on the whole system can be seen as an immediate feedback. Thus, the next step would be to enable users with full interaction inside virtual space. In practice, users will be able to interact with the models, add/delete more features or even change the direction of flow. The changes will be effective immediately on the system displaying inside VR.

On the basis of gathered results, investing more on improving the efficiency of VR content would benefit. Specifically, the order of information shared in VR space, the relevancy check of the data points, more intuitive ways of visualizing these data points and effectively design the information architecture of any content (here, the IoT concept) for VR. Moreover, importing fully interactive components will motivate users. The flexibility to modify the scale and position of the components will open new directions to explore. This exploration could be both in terms of context and VR as technology. In addition, users will feel immersed and present in the space when detached from real world disturbance. This can further be improved and made effective by adding examples and other relevant information. This also means to show every bit of information when users asks for it and not to overwhelm the user with all the data at one-go. The VR space should be tailor-made to user's level of knowledge.

One topic that was also raised from literature review, was the integration of actual IoT system in virtual reality. This could be a very important area to research in academics. This would allow practitioners work on real-time data and get hands-on experience with real feedback. Similar exploration was found in the research study conducted by Toumpalidis et al. (2018). The research describes *"How mixed reality can provide immersive view of information within the invisible layer of cyberspace"*. As part of a future work, they suggested to provide multiple users engaging with each other on different IoT devices and streams of data. This will require the capabilities of an actual IoT system, like, visualizing data points based on locations, analyzing big chunk of data and the list goes on. In this form, active collaboration can be formed between different disciplines and stakeholders.

Further investigation can be done on quantitative measurement as mentioned by the same paper. One of the challenges was to evaluate the data qualitatively, first with excel sheet then *Atlas.ti*. Although it helped in the end to analyze twice via different methods but it was time consuming and tedious work too. Another further investigation could be pedagogical design elements resonating the learning styles of each individual. Testing and measuring scale to test different aspects of UX must be considered too.

Chapter 6

Conclusions

After analyzing all five interviews and self-introspection of the whole journey, the following conclusions were constructed.

From background work, the lack of data visuals was highlighted as a potential problem for the programmers. The problem strongly relates to the full understanding of the process of developing an IoT application. Overall, the visualization of sensor data values has successfully impacted the users' apprehension. The provided environment was intentionally developed as a partial immersion to adhere to the main focus of the study which is the visualization aspect of VR. The case study chosen for this study was indoor air quality measuring system working on the principle of IoT. The system utilizes IoT technology to transform, store and analyze data. During the process, the relation between partially immersive visualization and user engagement with the environment was also studied. As a result of the usability testing, users appreciated and accepted the positive outcome of visualizing data inside a virtual world to better understand the *flow of data* in a system.

In a more thorough analysis, all the participants have at least enjoyed the VR experience and learned the basic components of the IoT system. The research further helped to explore the relation between the internet of things, immersive visualization, and user experience. As the main focus of the research study was to create a learning guide for developers, this prototype will be useful before starting to develop an IoT system. As mentioned in the Conceptual background chapter 2, the current research trend involves quite a combination of IoT technology and virtual reality in industrial work, utilizing the VR space to illustrate data acquired by IoT devices and their sensors, and so forth.

Learning the technical concepts using 3D visualization and partial immersive experience in virtual reality has helped the users to think beyond the formal limitations of the technology. All the users were benefited with the visualization of data inside a virtual space. A high level of curiosity and motivation was noticed at the beginning of the prototype. This enabled users to explore more about the air quality system and virtual world. All the test-users completed the tasks given in the prototype testing and as a result, they understood the *flow of data* via the static visualization of data within the virtual world. These interviews and hands-on experience encouraged users to try and think about the possibilities in the future. This could be in relation to learning, coding, and developing a complex system easily, quickly, and effectively. Here, easily refers to decrease in cognitive load, quickly reflects on time consumed to learn within virtual world, and effectively resonates the positive impact that lasts for long time after virtual experience, and effectively means the users' retention level. In addition, it opened up new avenues for users', either by uncovering related issues that are allied with development process or an entirely new insight. Likewise other technologies including augmented reality or mixed reality could have provided similar benefits like showcasing immersive visualization at different levels and interacting with the real products. However, augmented reality could not provide the two main advantages such as the feeling of being totally present within the scenario (remotely) and the flexibility to understand the concepts at the user's own pace.

This immersive visualization provides the benefit that someone with or without strong imaginative skills can perceive the visuals and grasp the system-level architecture of an IoT application development process. In addition, the user can relate to the virtual representation as duplication of the real-world IoT system and trust the environment. This boosts their cognitive skills to think beyond and explore new dimensions, such as, different protocol, database, or visualization tool that could be used to develop the actual IoT system effectively and efficiently. Hence, immersive visualization provides wider perspective to boost users' grasping skill.

Some of the guidelines to design the 3D visuals of components from IoT system were discussed in this study. For example, both text and image were required in virtual world but in some cases, only images were enough to convey the meaning of the content. The text should disclose the detail information based on users' flexibility. There is a possibility that the level of immersion can be varied depending on the context and end-goal. Moreover, the motion in immersive visualization can further help to explore and understand different characteristics of data. This could be one of the areas to research in future. The analysis highlighted that users seek for human-human communication, including sound or virtual avatar. In addition, animation loop of the flow could also be further potential research areas.

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Appendix A

Appendices

A.1 Interview questions

Questions asked to the IoT developer:

- **Developers work routine/process in general**
  - What is a typical day like for someone in this position?
  - What are the differences between that ideal day/week and the real world?
  - What part of [the job] do you most enjoy? What do you least enjoy?
  - How do you know when you are doing [the job] well?
  - What is the best thing about your job? What do you like best?
  - What do you like least with your job? What is the most stressful part?
  - What skills are required to do your job?
- **About the work itself, specifics**
  - How do you develop an IoT app? What are the steps you are following? (you can ask them to draw on paper if they want)
  - How do you ideate for an IoT app? (Can you show them to me?)
  - What kind of inputs do you receive when you start the work? In what format?
  - What are the challenges you face while interacting with IoT platform?

- **Working tools**
  - What platforms do you use to develop?
  - Can you tell me how you use [product]?
  - What does [product] allow you to accomplish that you otherwise could not?
  - Where does it fall short? What does not it do (or do well) that you need it to? What would an ideal experience with [product] be like?
  - What do you like, and what do you dislike about those tools?
  - Approximately how much time does completing such a task take?
  - What does completion mean in this case? What do you do with the information once you got it?
- **UX based questions**
  - Tell me about your last -How was your experience while developing an IoT app?
  - What challenges did you come across IoT development process? How did you solve it?
  - Why IoT based app for healthcare system?(one of the developer project).
  - What do you like the best about IoT (in general)?
  - How do you comprehend what is happening in IoT?
- **User expectation from IoT**
  - How would you like to understand IoT in future?
  - How would you like to see data flow in IoT?
  - What is the next great IoT experience in your view?
- **IoT data**
  - According to you, what is the role of data in IoT? What are its challenges?
  - Is it required to visualize data to understand the flow?
- **Virtual reality + IoT**

  - Any previous experience with VR?
  - If yes, then how would you imagine it's role in your daily work life?
  - Will immersive solution make any difference?
  - What can we do with VR in IoT?

- **Developers work routine:**
  - What is a typical day like for someone in this position?
  - How do you develop an IoT app?
  - How do you conceptualize the idea for an IoT app?
  - What are the challenges you face while interacting with IoT platform?
  - What platforms do you use to develop?
  - Ask developers what is natural to them when they code? Type of code or when they begin or when they come across an error?

Questions asked to the VR professional: VR designing practices and key points to remember while conceptualizing any VR concept. Virtual Reality design practices, immersive visualization, VR for enterprise solutions. VR design process along with the challenges you faced while prototyping. Aim: To learn how to start with VR concept and get experts insight.

- **VR Lecturer**
  - How do you start with VR concept?
  - After analyzing the problem/pain points of the user, how do you end up with VR solution?
  - Do you fit tech into their process/problems?
  - Tell me about the last case you created a VR solution. what drove you towards this kind of solution?
  - When talking about developers/coders in core enterprise development, do you think fully immersive solutions is apt?
  - What is your design process of a VR solution? Please describe the steps.
  - How do you form these design statements?

Questions asked to VR developers:

- **Your experience with VR**
  - How do you decide what needs to be shown inside VR environment?
  - How easy is it to understand what is shown inside the VR?
    * From creator's (developer/designer) perspective?
    * From end-user's perspective?
  - How do you measure / evaluate that user understood what's happening in VR?
  - Tell me about the last case you created a VR solution. what drove you towards this kind of solution?

- **Experience related (note: Here, people means end-user)**
  - How do people get started?
  - How do people experience VR?
  - What affordances are provided to guide people without overwhelming them?
  - How do you balance between providing too much guidance or creating a minimalist environment that does not overload the user with too many choices?
  - How often do you test your prototype with the right users?
  - About the technology:
    * Are people expecting the virtual experience to be as realistic as the physical one?
    * How far can we push those boundaries?
  - How do you measure / evaluate that user understood whats happening in VR?
  - Tell me about the last case you created a VR solution. what drove you towards this kind of solution?

- **VR with IoT**
  - How could VR help in enterprise solutions?
  - How VR environment help to understand IoT system and sensor network that are installed in the building?

  - How the VR world help to assess the behaviour/ functionality of the sensors on the building ?
  - What are the issues with data visualizations? Why visualizations are problem today?
  - How did you use VR to enhance the current status of data visualization?

- **VR concept creation**
  - How can I create content for VR prototype?
  - Being a developer, do you have any challenges? What are they and how you solve them?
  - Can you describe - how you deal with occlusion?

- **Usability testing**
  - Do you give users few minutes to get comfortable with VR environment or directly allow them to start interacting with the games/ apps that you have build?
  - What visual clues did you use to guide the user in VR?

A.2 Interview insights

There is a need to visualize invisible data in order to better understand data flow; avoid errors beforehand; look beyond the existing. It could be possible for the developers to explore if it makes easier to manage the connection and see how the processing of data takes place when visualized inside an immersive ambiance.

Initially, IoT solutions were combinations of several IoT endpoints, platforms, and data that flows in a coherent fashion across interfaces. Here, data could be generated through sensors, actuators, processors, embedded software,and may also belong to apps, analytics, machine learning, and short and wide range conection. From user interviews, it is seen that both direct and indirect stakeholders are aiming for better visualization in future IoT systems. Technicians, sales support providers, SPMs (product manager), team coaches are few examples of indirect users of the whole IoT system. Whereas, software developers, mobile/desktop application developers, platform developers and so on, are few examples of direct users of IoT system. (It would be good to know Market/team ratio of both direct and indirect users for one system.)

Team coach
"Focus on bigger picture of IoT and not only IoT portal, by this, I mean, include the whole IoT ecosystem, the journey, what comes before the IoT platform and what is after that. So, that the developers in our team get motivated of where the data is travelling and what will happen after they develop an application or user uses our portal".

Developer from a big-scale company
The size and scale of team also differs the experience of developing the IoT system.for instance, an application developed in a small team of 7-8 experts face different challenges as compared to a bigger organization. It becomes hard to coordinate with other departments/stakeholders of the platform as compared to internal team synchronization. Your hypothesis makes sense to me!! It would be better for developers to understand what they are working with. I do not understand much difference between augmented reality and normal video on mobile phone!! It will be useful for AR as tool of conveying the message, then it will be worth for everyone regardless if it a developer or any other stakeholder... Also, it depends on individual's learning style, are they visual learner or text-based learner.

Developer1 from a startup
Since, we have huge amount of data, it is important to figure out what parameters should be visualized on mobile or desktop app. Everything cannot be shown to the user within a single screen. Check what are the parameters need to be measured and how it should be seen on mobile phones?!. If we are measuring the flow of water, then how will we visualize it? Also, if we are measuring the level of water, in the sense like for tanks (that store the water) : it is required to know when the tank is getting overfilled or emptied. Because overfilling is wastage of water which is not good also the tank cannot be emptied because industry have some standards. Also, the unit matters. We need to think about everything that we want to monitor then think how to display those things. We cannot show level of water in centimeter or pulses or any other format(as we receive) but have to convert the data into the desired output form. For example: liters are used in industry, so we need to convert to that!.

Developer2 from a startup
Future IoT implemented from wide industry to day-to-day life. I would prefer to see raw data than visualized-accumulated data. Raw data refers every

second data but visualization or graph convey overall outcome. Data analyst or specialist will be user segment for raw data visualization.

Question: How the simulation will help you in VR? It will give you an idea of how the data is described. In 2D desktop, we defined how the data should look like but real-time visualization of actually the data looks will be interesting. It will also help us figure out how to show the same thing to our users. If we show every minute data in mobile app, it does not make sense. But, if we visualize every minute data in VR, it makes sense for us (developers). If we could virtually see the data and then understand how to implement the app further, then it would be really helpful.

Question: How VR could help the development process? Does it bring any difference? Right now, we think on our own and based on requirements, we work on the app and develop it. But, if we have virtual reality before actually developing the app, then it will be useful. Because we will get more idea! We will know what all works we have because we are already seeing it in VR and then make better decisions.

Developer from startup

Question: Is there a requirement to visualize invisible data? If yes, then when and how? It will better if at all I could see what data I am sending and receiving. It will help to build the app in better way and reduce the development time automatically.

VR developer

VR would provide immersive experience, depth = freedom of depth and make the developer understand the data flow better. Reduce development process, developer can avoid the errors before implementing the actual IoT system, it might open opportunities for developer to see things that they never thought before. To make the whole process in a better and efficient way.

Glossary

Active interactions	It is a type of interaction with digital products. The user consciously clicks a button and decides to interact with the device. For example, picking up an object in VR.
Actors	These are objects placed in a level in unreal engine.
Actuators	It is a component utilized as a converted in IoT system. It basically receives an input signal and transforms it into a physical action.
Meta-analysis	A form of secondary study where research synthesis is based on quantitative statistical methods.
Models	In the context of this thesis, this term refers to static mesh actors. These are one of the basic geometries that are rendered in Unreal Engine 4. The command Static Meshes can be dragged and dropped in the VR world from the Content Browser menu.
Natural interactions	These are real-world interactions implemented in a virtual world. The user interacts with the virtual space as they would interact in the real world. For example, drawing in VR space with the virtual brush as drawing with the paint brush in a real world.

Passive interaction	The interactions with the technology that does not require conscious input from the user. For example, turning the head to look around in a VR space is a passive interaction.
Primary study	In the context of evidence, it is an empirical study investigating a specific research question.
Secondary study	A study that reviews all the primary studies relating to a specific research question with the aim of integrating/synthesizing evidence related to a specific research question.
Skeuomorphic design	It is a design concept to reflect the real world objects especially, its look and feel in digital world.
System	The word *system* in this thesis refers to the internet of things (IoT) system. The IoT system is a complex system of interconnected devices and networks, exchanging data over the internet.
SLR method	A systematic literature review (often referred to as a systematic review) is a means of conducting intensive research. A form of secondary study that uses a well-defined methodology to identify, analyze and interpret all available evidence related to a specific research question in a way that is unbiased and (to a degree) repeatable.